STAFF REPORT 4

Environmental Sulphur Research in Alberta: A Review

Alberta
ENVIRONMENT
Research Secretariat

Sandhu et al., Environmental Sulphur
Research in Alberta: A Review

E R R A T A

p.iii	paragraph 3 line 3	"temperatures gradient" should be "temperature gradients"
p. 9	Table 2	Natural emissions in 1978 are 33700 t
p. 53	paragraph 4 line 1	"an" should be "on"
p. 54	paragraph 4 line 3	"consumptions" should be "consumption"
p. 58	paragraph 4 line 1	"studies" should be "studied"
p. 66	reference 19	"Environmentl" should be "Environment"
p. 89	second reference	"4th" should be "of the"

ENVIRONMENTAL SULPHUR RESEARCH IN ALBERTA: A REVIEW

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February 1980

PREFACE

Research into the environmental effects of sulphur emissions from gas processing plants and other industrial sources in Alberta has been underway for more than a decade, but no critical examination of all the available research information has been made. The present review attempts to meet the following objectives:

1. To compile a bibliography of published Alberta literature related to sulphur research;
2. To document total industrial sulphur emissions for the province;
3. To review and analyze available Alberta environmental research information; and
4. To identify future research needs.

The sections of this report were prepared by the following authors:

Sandhu - Introduction
Sandhu/MacDonald - Sulphur Emissions and Technology
Sandhu - Sulphur in the Air
Hammond - Effects in the Water
Sims/Hursey - Effects on Soil and Vegetation
Sandhu/Clanachan - Effects on Health
Sandhu - Miscellaneous Studies
Sandhu - Research Needs.

Overall co-ordination was the responsibility of the undersigned. Although sections were assembled by different authors, all the authors have reviewed the entire document. This represents an interdisciplinary team approach for preparing a review to identify future research needs.

Every effort was made to obtain all research and other related information available up to August 1979. However, it is probable that important papers/reports were missed or that the results of some are misinterpreted. The authors accept responsibility for such deficiencies.

In the literature different unit systems have been used for reporting results. Numerical results quoted in this review are in the units of the SI (metric) system and the original units are given in parentheses.

Many people, especially R. Peters and R. Rudolph, have assisted us in the preparation, review, editing, and typing of this document. We extend our sincere thanks to all of them.

Our special thanks are due to Dr. A. S. Clanachan, University of Alberta, for reviewing papers on animal and human health. Useful discussions with Dr. S. B. Smith are gratefully acknowledged.

February 1980 H.S. Sandhu

SUMARY

A review and analysis of published environmental sulphur research from Alberta have been carried out to identify future research needs.

Sulphur compounds are emitted into the atmosphere as gases and as particulates containing sulphates. Alberta industrial sulphur emissions (computed as elemental S) amounted to 313 and 275 thousand tonnes (kt) in 1974 and 1978, respectively. Natural sulphur emissions were estimated to be 34 kt in 1978. Published reports on technology from Alberta have dealt almost entirely with sulphur recovery from natural gas processing plants and oil sands plants.

In general, the dispersion of plumes is well estimated by acceptable formulas only when the plume layer can be characterized as homogeneous with respect to wind and temperatures gradient. Although wind shear and complex terrain tend to increase dispersion, localized areas of increased concentration can result. The presence of elevated temperature inversions inhibits vertical mixing and tends to increase ground-level concentrations.

Gas- and liquid-phase chemical reactions are most important in oxidizing SO_2. Reaction rates of sulphur gases are high in oil sands and electrical generating station plumes compared to gas plant plumes because of the presence of particulates. Sulphur gases and particulates are removed from the atmosphere by wet and dry deposition. Both mechanisms are important under Alberta climatic conditions, but account for the removal of only a portion of the total emitted industrial sulphur. Studies of rain and hail suggest that most of the sulphate in precipitation in central Alberta is of local industrial origin.

Waste waters from oil sands and sour gas plants contain sulphur compounds but their concentrations are within acceptable limits. Inorganic sulphur compounds appear to originate mostly from

natural geological sources. Given the present levels of sulphur emissions in Alberta and the buffering capacity of water systems, it is unlikely that any significant alteration of pH will occur in the near future.

While there are large areas of sulphur-deficient soils in Alberta, many of these are naturally acidic. Sulphur deposition from industrial sources cannot be relied on to alleviate sulphur deficiences. However, many sources are located very near to, or upwind of, soils and associated vegetation which are susceptible to damage by increased acidification. The analysis of sulphur isotope ratios is becoming an accepted method to correlate deposited sulphur with a specific source. In the past this correlation was difficult to determine. As well, the research establishing a correlation between sulphur deposition and its effects on soils has been inconclusive, due mainly to differences in methodology, environmental conditions, and measured parameters.

Physiological studies of vegetation in Alberta have been concerned with the effects of sulphur emissions on plant parts, individual plant species, and specific soil parameters such as pH. Very little is known about how these effects are reflected in the response of the total ecosystem and little consideration has been given to assimilative capacities of Alberta ecosystems.

Although investigations of health effects are few in number, they range from extensive multi-variable human and animal epidemiological studies to smaller laboratory studies using experimental animals. No association between the concentrations of sulphur gases found in the Alberta environment and adverse effects on the physical health of humans and animals has been proven. Higher concentrations of these gases, which may be present in an occupational setting or following an environmental emergency, undoubtedly do have the potential to cause adverse health effects in animals and man.

Future research needs for air, water, soils, vegetation, health, and environmental technology are identified.

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1. INTRODUCTION

It is well known that airborne emissions, such as sulphur oxides, hydrogen sulphide, nitrogen oxides, and heavy metals, can cause serious damage to the environment. Many examples of harmful ecological effects attributable to air pollution have been reported [1-10]. One of the most publicized and best known current examples is the ecological impact of acid precipitation.

The bulk of man-made sulphur emissions and their environmental impacts is concentrated in two regions: north-central Europe, and the northeastern United States and adjacent portions of Canada. It has been estimated that all global natural and man-made sources contribute between 100 and 170 Mt of sulphur annually to the atmosphere [3]; approximately 60% of this is now considered as being due to industrial activities. About 3 Mt of sulphur are emitted annually in Canada [11]. Industrial sulphur emissions in Alberta amounted to 0.27 Mt in 1978 [12].

Alberta is one of the richest natural resource provinces in Canada. Large deposits of fossil fuels, such as natural gas, oil, and coal, are found inside its boundaries. The processing of these resources results in the release of sulphur and various other emissions to the environment. Over the years, the Alberta Energy Resources Conservation Board (ERCB) has compiled, analyzed, and assessed the available information on these resources [13-17]. In addition to its other responsibilities, the Board maintains a close liaison with various industries and their associations.

To date, the natural gas processing industry is the major source of sulphur gas emissions in Alberta. Because of the environmental, social, and economic concerns of Albertans, the Environment Conservation Authority of Alberta (ECA), now the Environment Council of Alberta, held public hearings in 1972 on the environmental effects of sulphur extraction gas plants in Alberta. Background

material, recommendations, and proceedings of the ECA have been published and are available to the public [18-20].

Through various Acts [21-24], the Alberta Department of the Environment has been charged with the co-ordination of policies, programs, services, and administrative procedures of all government departments and agencies in matters pertaining to the environment. The Department has an overall responsibility for pollution control and environmental standards [22, 23]. Informational letters, guidelines, and monitoring directives are issued to the industry from time to time [25-29].

Various funding agencies, individual industries, and industrial groups, such as the Whitecourt Environmental Study Group (WESG) and the Oil Sands Environmental Study Group (OSESG), have funded research investigations to assess the impact of sulphur gas emissions on components of the ecosystem. These studies are reviewed in the appropriate sections.

A joint research program by the governments of Alberta and Canada, the Alberta Oil Sands Environmental Research Program (AOSERP), was undertaken in 1975 to assess the impact of present and future industrial developments on the oil sands area of Alberta [30]. Recently, an interim AOSERP report covering the period 1975 to 1978 has been published [31]. In March of 1979, the Government of Canada terminated its participation in AOSERP; Alberta Environment is continuing a major environmental research effort in the oil sands area. To date, more than 140 AOSERP reports have become available. Relevant research studies are reviewed in various sections of this document.

In order to improve the exchange of new research information, three Alberta Sulphur Gas Research Workshops were organized and the technical proceedings of these workshops published [32-34]. However, a review of available research information has not yet been carried out. This report attempts to fulfill this need.

As mentioned earlier, excellent reviews and conference proceedings covering worldwide literature on sulphur emissions and

their effects on the environment have been published in recent years [1-10]. Since the prime objective of this study is to review environmentally related sulphur research in Alberta, no attempt is made to review those reports published elsewhere.

The review is not meant to be exhaustive in presenting details of specific research. Its aim is to consolidate the wealth of research and related information generated in Alberta for use by industry, government, and others. It is believed that this approach will aid resource managers, and the public in particular, in understanding the current knowledge of the effects of sulphur emissions in Alberta.

2. SULPHUR EMISSIONS AND TECHNOLOGY

Improvement in sulphur recovery technology over the years has been accelerated by attempts of regulatory agencies to improve environmental protection through reduction of sulphur emissions at their sources. This has prompted researchers to examine the basic process for sulphur production from hydrogen sulphide, the Claus reaction (Section 2.2), to examine incinerator and stack characteristics, and to develop methodologies for increased recovery through Tail Gas Clean Up (TGCU). This section on sulphur emissions and technology provides an overview of research developments undertaken in Alberta.

2.1 EMISSIONS

A number of sulphur compounds are emitted into the atmosphere by various industrial sources; however, most of the sulphur emissions are in the form of sulphur dioxide (SO_2). The term "sulphur gas emissions" is used when discussing sulphur compounds generally; specific compound names, such as SO_2, hydrogen sulphide (H_2S), carbon disulphide (CS_2), and carbonyl sulphide (COS), are used when discussing specific components. Industrial emissions from individual sources for Alberta for the period 1974 to 1978 have been reported previously [12]. A summary of these emissions is given in Table 1. Figure 1 displays the location of major emission sources. These sources are widely distributed in Alberta, but tend to be concentrated more heavily in the western half of the province.

The main sources of SO_2 emissions are natural gas processing plants, including extraction and flaring gas plants. Total estimated daily emissions from these two plant groups amounted to 447 t (422 + 25, see Table 1) of sulphur during 1978.

The Suncor, formerly known as Great Canadian Oil Sands, and Syncrude Canada plants are the only two industrial sources of sulphur emissions in the Athabasca Oil Sands area at the present time,

Table 1. Observed sulphur emissions (tonnes/day) from industries operating in Alberta for the period 1974 to 1978. The number of plants are given in parenthesis.

SOURCE	1974	1975	1976	1977	1978
Extraction Gas Plants	614.0[a] (41)	589.7 (42)	443.9 (43)	429.3 (43)	422.2 (43)
Oil Sands Plants	131.1 (1)	124.8 (1)	125.8 (1)	112.3 (1)	147.4[b] (2)
Sour Oil Production Facilities	N/A	N/A	N/A	N/A	54.7[c]
Power Plants	31.7 (4)	37.7 (4)	44.3 (4)	43.8 (4)	48.0 (4)
Flaring Gas Plants[d]	23.0 (19)	24.3 (22)	26.1 (23)	21.7 (26)	24.6 (28)
Refineries	33.2 (6)	26.5 (5)	21.8 (5)	21.8 (5)	21.8 (5)
Pulp & Paper	N/A	N/A	18.7 (2)	10.2 (5)	10.3 (5)
Fertilizer Plants	20.2 (4)	18.5 (5)	8.6 (5)	10.2 (5)	10.3 (5)
Other	3.8 (2)	7.1 (2)	9.7 (2)	10.0 (2)	6.0 (2)
TOTAL	857.0 (77)	828.6 (81)	698.9 (85)	670.4 (88)	753.7[e] (91)

[a] Mutiply these values by a factor of 2 to obtain SO_2 emissions. All figures are based on 365 days.
[b] Maximum allowed by licence is 323 t. Syncrude began production in mid-1978; emissions will be higher in 1979.
[c] Total number of sources included in this estimation is 324. Total estimated emissions for 1974 to 1977 do not include emissions from sour oil production facilities. It is reasonable to assume that these facilities had emissions similar to 1978 during previous years.
[d] Flaring gas plants do not recover sulphur, but burn all sulphur compounds extracted from the natural gas.
[e] Total number of sources in this estimation does not include sour oil production facilities.
N/A - Not Available.

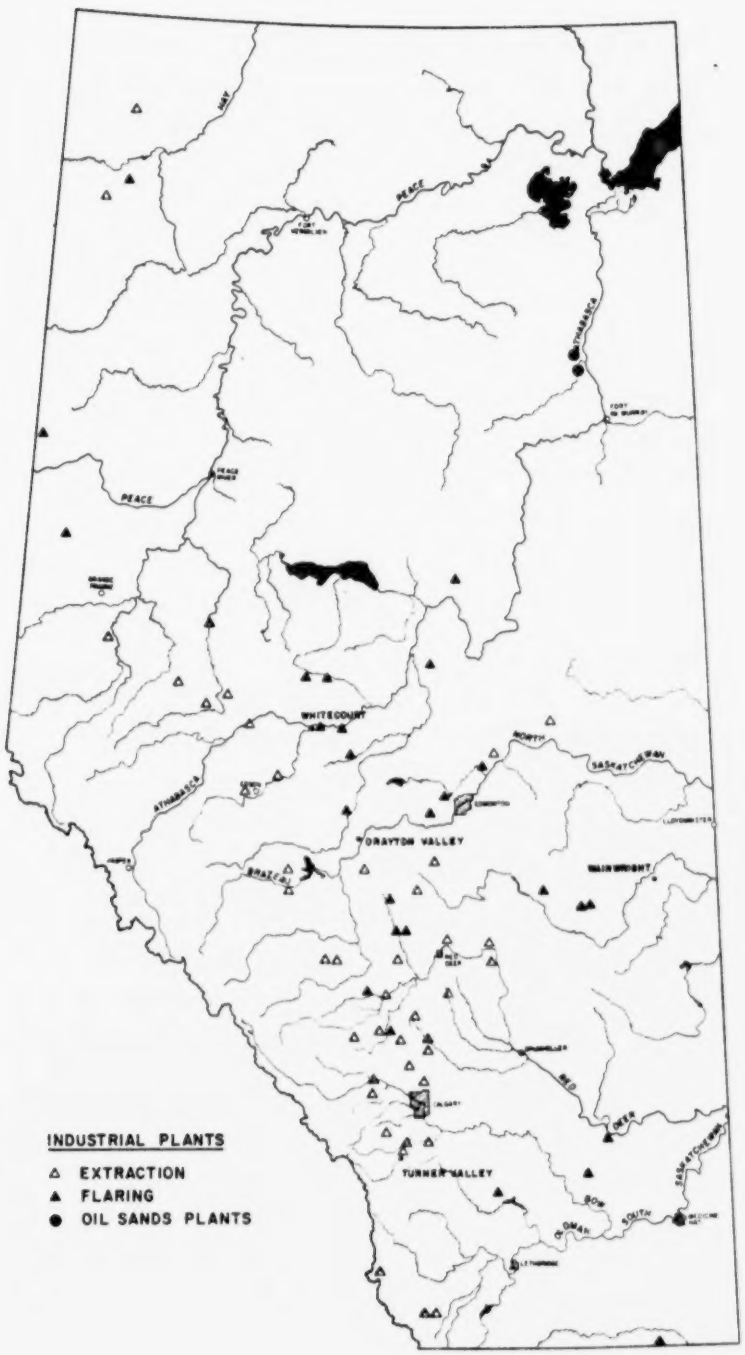

Figure 1: Major sulphur emission sources in Alberta.

with daily total emissions of 147 t (maximum allowable by licence is 323 t) in 1978. Since Syncrude Canada started production of synthetic crude during the summer of 1978, total emissions will be higher in future. Both these plants employ hot water extraction technology which was pioneered by Clark to recover bituminous material from oil sands [35]. Three sources, namely the powerhouse, sulphur incinerator, and flare, contribute to the total emissions from Suncor [12].

Other significant sources of sulphur emissions exist in Alberta. A large number of sour oil production facilities (batteries) located throughout the province have emissions estimated at 55 t per day. There are only four coal-fired power plants operating in the province and their total sulphur emissions are 48 t per day. It is important to note from Table 1 that less than 10% of the emitted sulphur is from sources included in the categories of refineries, fertilizer plants, pulp and paper mills, and other industries.

Total sulphur emissions, as well as emissions from two types of major point sources for a five-year period, are shown in Figure 2. Both licensed and observed total emissions have remained near 0.5 and 0.3 Mt per year, respectively, even though the number of sources increased from 77 to 91 (Table 1). The decrease of emissions from sour gas plants is significant. This reduction has been realized by the imposition of more stringent requirements by the Alberta Department of the Environment. The Department now requires that all plants install the best practicable technology available at the time plant design is fixed in order to minimize sulphur emission.

Annual sulphur emissions and estimated amounts of sulphur fertilizers (tonnes) sold in Alberta are given in Table 2. About 75% of the sulphur used in fertilizer is in the form of ammonium sulphate, 20% is calcium sulphate (impurities in phosphate fertilizer), and 5% is elemental sulphur. Obviously, amounts of sulphur fertilizer and natural emissions are much smaller than industrial sulphur emissions in Alberta.

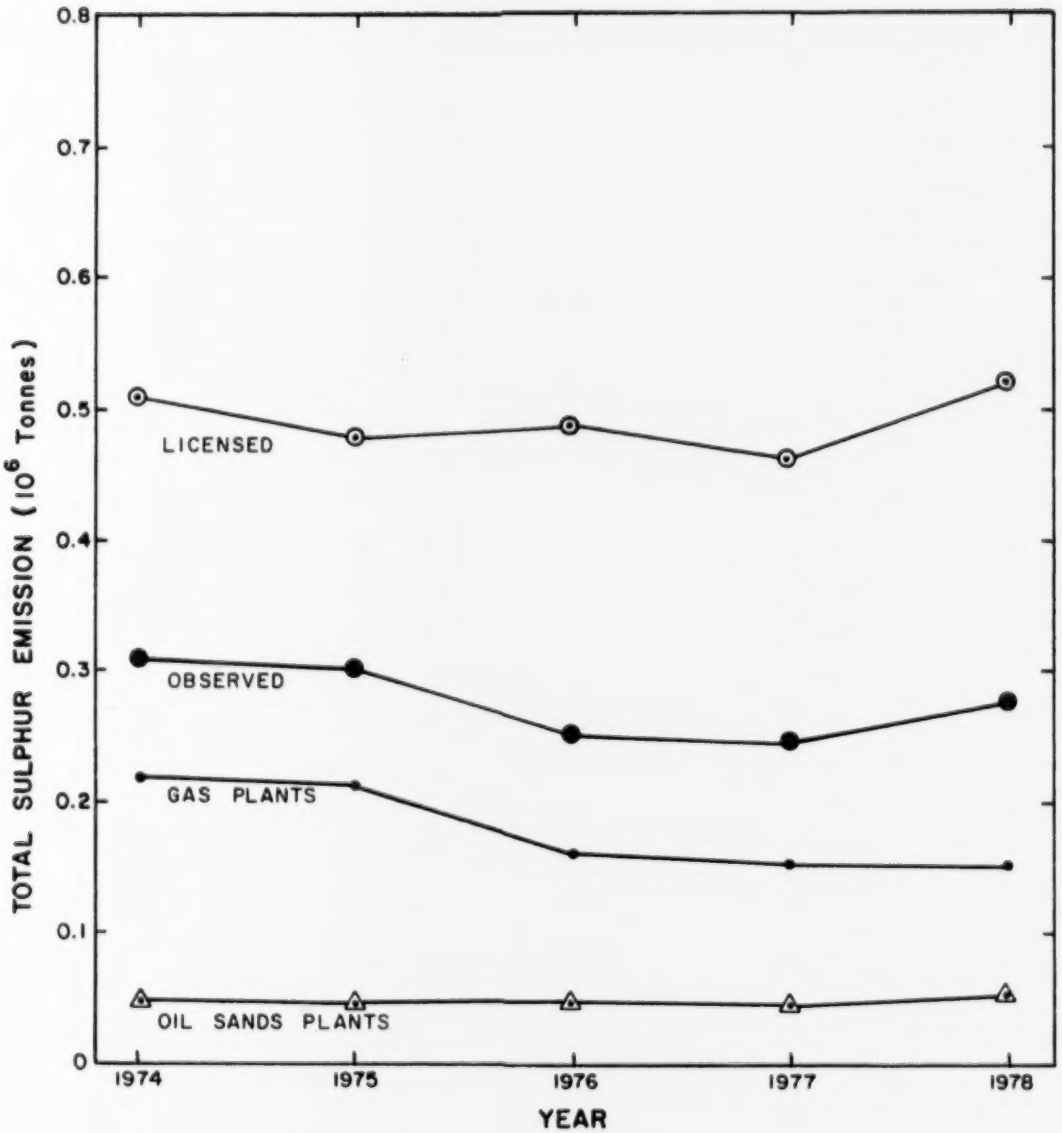

Figure 2. Industrial sulphur emissions in Alberta, 1974 to 1978 [12].

Table 2. Sulphur emissions and sulphur in fertilizers (tonnes) from Alberta for the period 1974 to 1978.

SOURCE	1974	1975	1976	1977	1978
Industrial Emissions[a]	313 000	302 000	255 000	245 000	275 000
Natural Emissions[b]	N/A	N/A	N/A	N/A	N/A
Fertilizer (S)[c]	21 500	20 900	20 400	18 900	17 300

[a] Sandhu [12].
[b] Canada Department of the Environment [234].
[c] Penney [235].
N/A - Not Available.

Because of energy priorities, the development of oil sand deposits represents a major future source of sulphur emissions. It is not possible to estimate the impact of sulphur emissions as a consequence of developing this resource because, as yet, there is no indication of future plant numbers. However, it is expected that the trend of technological improvement demonstrated by the two operating plants will continue, and that the amount of SO_2 emitted by additional planned plants will be reduced relative to present emissions. The improvements experienced to date are illustrated best by expressing the emission rate related to the amount of bitumen processed by the plant. The emission rate for the first oil sand plant is 13.5 t S/1000 m^3 (27 t SO_2/1000 m^3) of bitumen processed, for the second plant it is 4.8 t and for the proposed plants the sulphur emissions fall in the range of 1.2 to 2.4 t S/1000 m^3 bitumen.

Recently, some projections about sulphur emissions from Alberta energy industries have been published. Figure 3 shows the total annual and cumulative sulphur emissions from some industry groups and also the contributions of each group. Figure 3 demonstrates that certain Alberta industries, especially the energy industries, emit substantial and increasing quantities of sulphur into the atmosphere. By the year 2006, annual emissions could be twice the 1978 emissions; cumulative emissions could reach approximately 21 Mt (19 million long tons), or three to four times the current cumulative amount [36].

2.2 SULPHUR RECOVERY TECHNOLOGY

No attempt is made to present a complete examination of sulphur recovery technology, since the main emphasis of this review is on the environmental aspects of sulphur research; however, it is important to understand the developments leading to emission control. Research in Alberta has concentrated almost entirely on natural gas and oil sands plants; therefore, this summary will relate only to these industries.

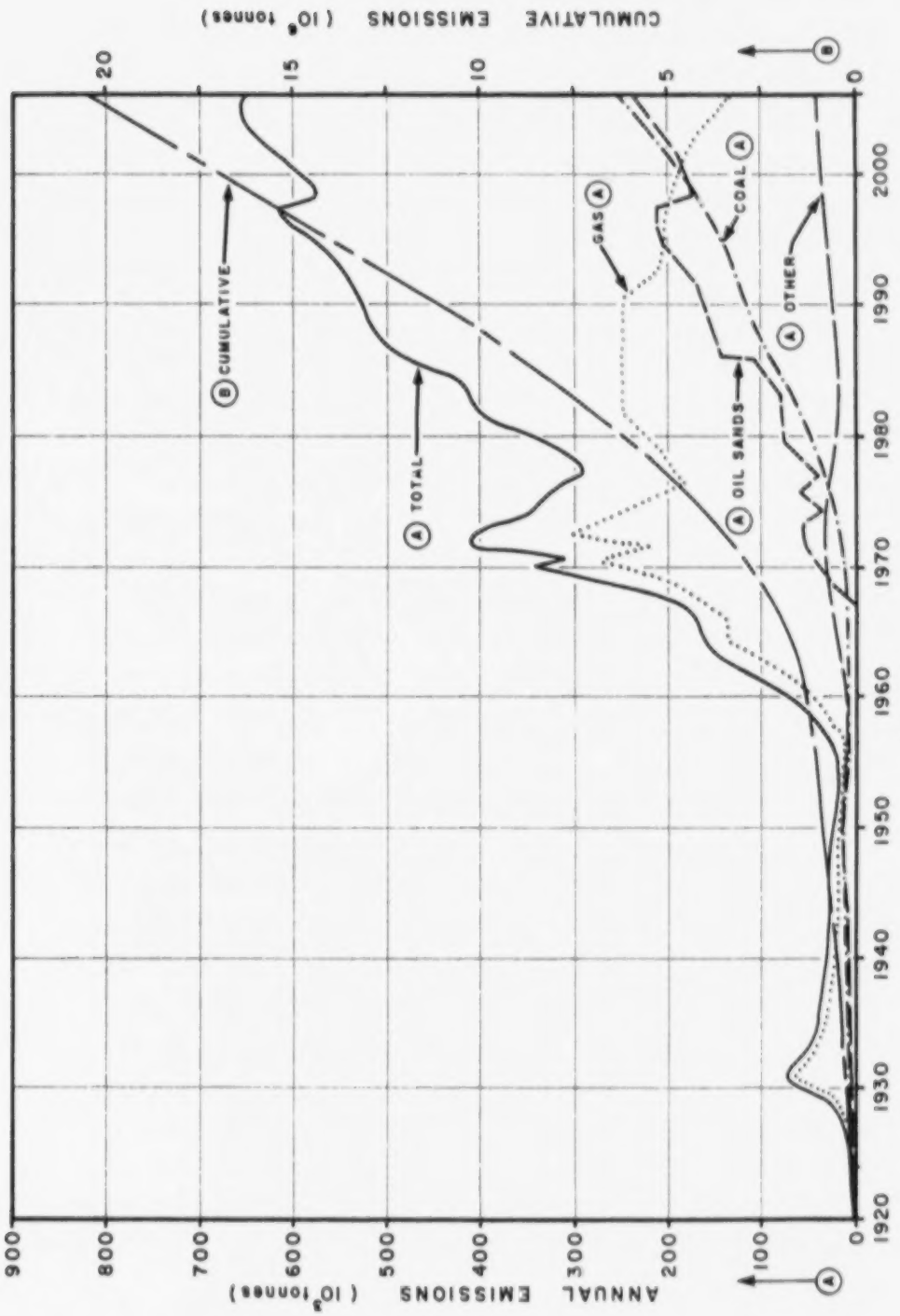

Figure 3. Annual and cumulative sulphur emissions from energy industries in Alberta, 1920 to 2006 [36].

2.2.1 Sour Gas Plants

All natural gas contains some H_2S. The designation "sour" gas is based on pipeline specifications, the gas being sour if it contains more than 0.016 mol H_2S/1000 mol natural gas. With higher concentrations, this gas must be treated to remove the H_2S which, depending on the concentration, either is sent to flare, or goes through a recovery process. The recovery process can be considered in various stages, as described below.

2.2.1.1 The sulphur plant. All sulphur recovery operations in Alberta are based on the modified Claus reaction [37, 38]. The two basic reactions involved in the conversion of H_2S to elemental S are:

$$2H_2S + 3O_2 \longrightarrow 2SO_2 + 2H_2O \qquad (1)$$

$$2H_2S + SO_2 \rightleftharpoons \frac{3}{n}S_n + 2H_2O \qquad (2)$$

where n represents the equilibrium average molecular species of the sulphur vapor product. Reactions (1) and (2) occur homogeneously in a burner preceding the catalyst beds, while reaction (2) occurs alone in the beds. Other reactions which occur as a result of hydrocarbon or CO_2 contamination of the acid gas lead to the production of COS and CS_2, which may foul the catalyst or be of concern in the incineration process.

Kinetics, thermodynamics, and catalyst properties relevant to the Claus process have been investigated extensively [39-49]. These investigations have produced rate expressions for SO_2 conversion, a better understanding of reaction mechanisms, and an awareness of improved operating conditions. In addition, criteria for optimum operating conditions in a Claus reactor have been developed which predict a 99.4% thermodynamic recovery of sulphur with a 4-stage unit; actual field trials with a new catalyst gave a 99.1% recovery [50]. In the same paper, it was stated that the persistent problem of catalyst deactivation with time would decrease recovery efficiencies.

2.2.1.2 Incineration of tail gases. Waste gases leaving the Claus reactors are emitted eventually to the atmosphere after being burned in an incinerator or passed through a TGCU unit for additional sulphur recovery, and then incinerated. The effectiveness of the incineration to reduce all sulphur compounds to SO_2 has been of concern for controlling emissions; proper burning characteristics and stack emission temperatures determine the fuel consumption in this incineration step. Laboratory and field studies have been undertaken to determine conditions which would minimize fuel consumption and, at the same time, meet air quality standards [45, 51]. The thermodynamics of the system and oxidation kinetics of the combustible species have been determined. Results have indicated that stack top temperatures could be reduced below the regulatory 538°C (1000°F) and still stay within air quality guidelines (0.2 ppm SO_2 averaged over 0.5 hour), resulting in a fuel saving. For one plant, an exit temperature of 496°C (925°F) resulted in a fuel saving of 40% (below this temperature, fuel consumption would increase).

2.2.1.3 Sulphur recovery from waste gases. With improvement in technology, and as a result of increased public concern for environmental protection, the Alberta ERCB in 1971 set out recovery efficiencies to be attained at sulphur recovery plants. As a result, several plants in Alberta now have TGCU units installed to recover additional sulphur not removed in the Claus convertors. Recovery efficiencies now vary from 90 to 95% for a 9 to 90 t/day (10 to 100 tons/day) plant to a maximum of 99% for a 900 to 3600 t/day (1000 to 4000 tons/day) plant. Actual research and development of this technology occurred outside of Alberta; however, reports from Alberta on operating conditions have appeared in the literature [52-54]. Reviews of various TGCU processes have been prepared [55-58].

The use of carbon monoxide (CO) as a reducing agent for SO_2 in wet stack gases has been reported [59, 60]. Bench scale experiments were able to remove a maximum of 90% of the SO_2 in the wet stack gas, but side reactions produced COS and H_2S. Efficiency

of removal was very dependent on H_2O and CO concentrations and on temperature. Complexity of the process is increased by several competing reactions, notably that of H_2O and CO; the water gas shifts the reaction equilibrium.

2.2.2 Oil Sands Plants

Emissions from oil sands plants come primarily from the sulphur plant and the power plant (Suncor uses coke containing approximately 6% sulphur for power production). The sulphur plant is basically the same as a sour gas plant using the Claus process.

A review has been published dealing with the suitability of various pollution abatement technologies for oil sands plants [61]. TGCU units were examined for their adaptability to oil sands operations. Only three processes were considered to have the proven technology and those were based on oil refinery applications. Because of problems inherent in oil sands operations and the larger scale required, it was concluded that tail gas clean up would not be feasible. Power plant emissions require different technologies than TGCU; flue gas desulphurization (FGD) has been developed primarily for use in coal-fired electric generating stations for SO_2 and particulate removal. In 1976, one technology, using limestone in a non-regenerative process, was considered as a possible FGD candidate. Drawbacks of the process were: uncertain economics, disposal area requirements for the slurry, potential groundwater problems, flue gas reheating, and increased energy consumption. The general conclusion of this study was that best practicable technologies are already in use in presently operating oil sands plants.

A later study also investigated FGD technology as it would apply to the Suncor plant [62], as the company would be required to reduce power boiler particulate emissions from 3.7 g/standard cubic metre (SCM) [1.6 grains/standard cubic foot (SCF)] to 0.37 g/SCM (0.16 grains/SCF) by mid-1979. For particulate removal only, electrostatic precipitation was recommended over wet scrubbing. For SO_2

removal from the boiler stack, the report recommended a wet scrubbing, non-regenerative process. Problems associated with this process have been described above.

Best practicable technology as well as novel technology for air pollution control have been discussed for the Syncrude plant. It was postulated that the "effective" source height of the plume could be increased by reducing entrainment of ambient air. This would decrease the ground level concentration expected under normal operating conditions. The suggested method consisted of a device in the stack which would allow the gas to flow from the exit in concentric rings of decreasing velocity from the centre to the edge. This would reduce entrainment of ambient air into the plume and as a result would preserve plume velocity and temperature. Experimental verification of this proposal was not provided [63, 64].

2.3 GAS WELL BLOWOUTS

There have been two reports prepared on gas well blowouts in Alberta where environmental effects have been examined. The New Norway blowout occurred in 1973 [65]. On-site investigations indicated that there was no major impact on wildlife, livestock, vegetation, and human health. Long-term monitoring was not undertaken.

A blowout in the winter of 1977-78 near Drayton Valley was monitored mainly for effects of H_2S gas on humans [66]. The winter conditions existing at the time were considered to have minimized any effects of gaseous or liquid emissions on other environmental components and, other than odour, no significant effects were found.

3. SULPHUR IN THE AIR

Sulphur compounds released into the air are subjected to three atmospheric processes: (1) transport; (2) chemical transformations; and (3) removal. Published studies from Alberta have provided increased understanding of these processes from different sources under various topographic and atmospheric conditions.

3.1 TRANSPORT

Most of the studies investigating the diffusion process have dealt with sulphur dioxide plumes generated by incinerator stacks at sulphur recovery plants or by the powerhouse stack at oil sands plants. Only a few studies have dealt with other sources including electrical generating station plumes and pipeline ruptures. In general, diffusion studies are of three types: those relating to observation and measurement of plume parameters; those relating specifically to diffusion over complex terrain; and those modelling the diffusion process mathematically. A review of current knowledge of plume dispersion and diffusion characteristics in Alberta is in preparation [67]. To date, long- or medium-range transport of sulphur compounds into and out of Alberta has not been investigated.

3.1.1 Sour Gas Plants

A number of gas plant plume dispersion studies have been published. The majority have attempted to describe or measure the dispersion of plume at some distance downwind of the source either at ground level or at various levels throughout the vertical extent of the plume [68, 69]. Visible tracers, both natural and man-made, have been used to improve the contrast and resolution of photographic records of plume dispersion. Ultraviolet photography relying on absorption by SO_2 has been used for plume tracing near the stack [70].

Since some of the major gas plants in Alberta are situated in the foothills, the effects of complex terrain on diffusion under a variety of atmospheric conditions have been studied [71-76]. Wind tunnel studies of diffusion near two-dimensional hills have indicated that ground level concentrations can increase (relative to flat terrain) in the stagnation area upwind of slopes. The increase was less than 20% for gently rolling terrain but 100% or more for steep slopes [77].

Wind measurements suggested that, for moderately sloping terrain, the windflow is parallel to the ground. In addition, turbulence levels over irregular terrain were higher than over flat terrain. This implies that effective diffusion coefficients will also be larger over complex terrain [78].

Aerial SO_2 concentrations from sulphur recovery plants were measured during both normal operating and flaring conditions. It was found that plume elevation was well predicted by the Briggs formula for a stable, stratified atmosphere and that SO_2 concentration levels remained below the regional air quality standard, even under flaring conditions, provided that the mixing height of the atmosphere was above 1100 m [79].

Sulphur dioxide concentrations measured near sulphur recovery plants have been used to determine the applicability to Alberta situations of popular diffusion estimation formulas [80-82]. In particular, the expressions of Pasquill, Sutton, and Bosanquet have been applied to maximum ground level and centreline concentration calculations and plume dispersion as functions of downwind distance and time. It appears that, under uniform conditions in the plume layer, these expressions yield meaningful results. Better correlation between predicted and observed concentrations can be achieved by "matching" the observed and theoretical plume spreads to account for local topography and atmospheric anomalies. Under non-uniform conditions when wind direction shears or temperature inhomogeneities exist, pollutant concentrations, in general, are not well predicted by these relations. Since the highest ground level concentration events occur in situations related to the presence

of inversions (fumigation, inversion break-up, or trapping), it is important that diffusion under these conditions be well understood.

Because the atmospheric and topographic conditions under which pollutants are transported are not simple, some effort has been made to model plume diffusion numerically [83, 84]. Capabilities of these models included the use of multiple sources through superposition, complex terrain and time-dependent winds utilizing modified potential flow, and the ability to handle inversion break-up. Diffusivities were determined by matching observed and predicted concentrations.

An in-depth study has been carried out of the different aspects of the numerical prediction of plume diffusion. Two models were developed, one for flat ground and one capable of handling abrupt changes in terrain downwind of the source. Among the topics investigated was a comparison of analytical and numerical methods. Discretization errors (the difference between analytical and numerical predictions) can be very large but can, in general, be minimized by using an optimum grid size. Discretization errors decreased with increasing distance from the stack and with increasing diffusivities [85, 86]. It was also shown in the same study that simple methods of plume rise estimation appear to be as accurate as more complicated methods. Temperature lapse rate was a poor indicator of dispersion based on Pasquill stability class especially under chinook conditions or for windspeeds greater than approximately 3 m/s (10 mph). It was suggested that the frequency of occurrence and height of inversions must be taken into account and that the possibility of plume overlap cannot be overlooked.

It should be noted that all of the above studies were concerned with short-range diffusion, at distances less than approximately 10 km downwind of the stack. Investigations of medium- and long-range transport should be of high priority in the future.

3.1.2 Oil Sands Plants

Much of the research related to sour gas plant plume rise and diffusion is applicable, with minor modifications, to oil sand stack plumes. The quality of ambient air near the oil sands area has been investigated. The background SO_2 concentration was found to be about 0.001 ppm; nearer the source this increased to 0.003 to 0.006 ppm (these numbers are tentative and should be used with caution since the lower detectable limit of the monitoring instrument was 0.005 ppm). No change in total sulphur was observed from 1974 to 1977 [87].

Since the height of the inversion base directly influences maximum concentrations, methods of determining the height of the thermal boundary layer have been investigated and a numerical model has been developed [88, 89]. The predicted heights had an annual and diurnal variation. The model described the trend but not the details of the height increase with time in the morning and early afternoon hours. Predictions for late afternoon were not accurate because it was not possible to model entrainment realistically.

Some studies of plume dispersion in the oil sands area have been published [90-95]. Two winter field studies identified some of the unique features of the area near the Suncor plant which is located in the Athabasca River valley [93, 94]. Under inversion conditions, winds in the valley decoupled from winds aloft. The flow and ground-based emissions tended to follow the valley axis. During neutral and unstable conditions, no decoupling occurred. Of the several formulas examined, those of Briggs and Holland best estimated plume rise. The Tennessee Valley Authority (TVA) scheme for vertical spread and the Pasquill-Gifford scheme of horizontal spread were the best estimators of plume dispersion [94].

In a 1976 study, airborne measurements of plume and turbulence parameters were made [95]. The observed plume spread was compared to that predicted from the Pasquill curves for the appropriate stability class. It was found that the lateral standard deviation of plume spread was larger than predicted, possibly due

to plume overlap. In the presence of an elevated inversion, the vertical standard deviation was less than predicted. Both horizontal and vertical plume spread varied roughly as the square root of time, as predicted by Taylor's theory. No topographic influence was observed at typical plume centreline heights.

Plume dispersion data in the oil sands have been examined critically and synthesized. Wind direction shear was shown to have three distinct effects upon a plume: change in bearing of the plume as it rises; distortion of the plume cross-sectional shape; and enhanced dispersion. In the buoyancy-dominated region, the ratio of horizontal plume spread to vertical plume spread was found to be 1.4. In the environmentally dominated region, the horizontal plume spread was best estimated by the schemes using wind direction fluctuation measurements while the vertical plume spread was estimated adequately by the TVA scheme [96].

Using a Gaussian plume model, general expressions for the maximum and critical ground level concentrations have been developed [97]. These expressions are analytic, requiring only a hand calculator for solution.

Equations of the conservation of mass, energy, and vertical momentum have been solved for the rise of buoyant plumes in calm conditions with particular emphasis on the effects of drag and entrainment [98]. Most of these solutions are also analytic.

A Gaussian model applied to meteorological data in the oil sands area predicted that the concentration of SO_2 resulting from the operation of the Syncrude 180 m (600 ft) stack would be lower than 0.2 ppm 98.6% of the time, based on the daily permitted emission rate of 145 t of sulphur (3363 g/s SO_2). The value of 0.2 ppm is the maximum 0.5 hour average concentration of SO_2 as allowed by the Clean Air Regulations (Table 3). Concentrations larger than 0.2 ppm were associated mostly with fumigation or inversion break-up conditions [99].

The results of a model designed to calculate annual average SO_2 concentrations using the assumptions of flat terrain and a homogeneous atmosphere indicated that the annual average SO_2 concentration

Table 3. Alberta air quality standards and national air quality objectives for sulphur gases.

CONTAMINANT	ALBERTA STANDARDS[a]	FEDERAL NATIONAL AMBIENT AIR QUALITY OBJECTIVES[b]		
	ppm ($\mu g/m^3$)	Max. Tolerable ppm ($\mu g/m^3$)	Max. Acceptable ppm ($\mu g/m^3$)	Max. Desirable ppm ($\mu g/m^3$)
Sulphur Dioxide				
Annual arithmetic mean	0.01 (30)	-	0.02 (60)	0.01 (30)
24-hour average	0.06 (150)	0.31 (800)	0.11 (300)	0.06 (150)
1-hour average	0.17 (450)	-	0.34 (900)	0.17 (450)
0.5-hour average	0.20 (525)	-	-	-
Hydrogen Sulphide				
24-hour average	0.003 (4)		-	-
1-hour average	0.010 (14)		-	-
0.5-hour average	0.012 (17)		-	-

[a]Government of the Province of Alberta [236].

[b]Federal-Provincial Committee on Air Pollution [237].

resulting from Suncor and Syncrude emissions was 0.008 ppm (21 $\mu g/m^3$). Concentrations were insensitive to the half life of the SO_2. Removal was estimated to decrease concentrations by 10% [100].

The effects of lateral wind shear on horizontal plume dispersion have been modelled. It was found that directional shear increased dispersion and that the downwind distance where shear effects become dominant (typically beyond 5 km) is a function of stability. Under shear conditions, the effect of variations in stack height was more extreme [101].

The steady state diffusion equation has been solved numerically using a concentration-moment technique. Increasing surface roughness increased plume dispersion. The effect of variations in stack height on dispersion was influenced by the vertical profile of the diffusivities. The numerically obtained plume spreads were shown to be qualitatively similar to those determined experimentally [102].

Although several studies have included the effects of multiple sources downwind of plants in the oil sands area, a comprehensive air quality model of the entire oil sands area, including diffusion, topography, and chemical interactions, has yet to be developed. Future investigations should be directed toward these aspects, as well as to the transport of air pollutants out of this region.

3.1.3 Other Sources

Among other sources of atmospheric sulphur, power plants are most important. However, very little research has appeared in the open literature in Alberta specifically related to the diffusion of electrical generating station plumes. It has been found, however, that relations for plume rise and dispersion valid for gas plants are also valid for electrical generating stations [103].

Another source of atmospheric sulphur, although rarely occurring, is sour gas pipeline ruptures. One model study found that line pressure and initial line volume had a major influence on the distance to a given concentration. Gas temperature, molecular weight,

valve closure time, and throughput had little effect. Plume rise and blow-down rate were important variables [104]. An analytical assessment indicated that a double exponential blow-down could be used to form an "effective plume" for calculating dispersion. Self-generated turbulence was found to increase concentrations by more than 30%. Indoor concentrations were less than 10% of those outdoors [105].

Some characteristics of pipe bursts were investigated in a field study. Several different rupture types were observed, each creating a different size and shape of crater (the pipes were below ground). The shape of the crater determined the initial shape of the plume. Because of the rapidly decreasing release rate, plume configuration was time-dependent. Based on observations, the assumption of a vertical jet release was found to be invalid [106].

3.2 CHEMICAL TRANSFORMATIONS

Brief and exhaustive reviews of the atmospheric chemistry of SO_2 have been carried out to assess the importance of chemical transformations under Alberta climatic conditions [107-112]. The relative oxidation rates of SO_2 are highly dependent on the nature and composition of the polluted atmosphere, solar radiation, and meteorological parameters. Direct photo-oxidation of SO_2 is theoretically a viable mechanism but now is believed to be of marginal significance. Instead, the oxidation of SO_2 in the atmosphere is thought to evolve from two distinctly different types of reactions: 1) gas phase reactions involving photochemically created small free radicals such as HO, HO_2, and CH_3O_2; and 2) liquid phase reactions (clouds, aerosols) in the presence of metal ions and other dissolved gases such as NH_3, O_3, and H_2O_2. The relative importance of gas-phase and liquid-phase chemistry is presently uncertain and the subject of intense research efforts around the world.

Experimental and modelling studies on the chemistry of SO_2 and other sulphur compounds in the Alberta troposphere are scarce. Although sour gas processing plants are the major sources of industrial

sulphur emissions, only one study has been reported on the short-range chemistry of their stack plumes [113]. Airborne sampling from a helicopter was used. The researchers developed and employed a conserved gold tracer technique to obtain a directly measurable dilution factor for the SO_2 gas downwind of a plant emitting about 62 t of sulphur (124 t of SO_2) daily. There were not enough data points to make a definitive statement on the oxidation rates of SO_2 within the short range studied. Additional experimental work is needed to quantify short-range SO_2 oxidation rates.

In a 1977 field study, undertaken in February and June [114], the rate of SO_2 oxidation to sulphate particulates from the Suncor power plant stack was found to be low during the month of February and in early mornings in the month of June, typically less than 0.5% per hour. Later during the day in June, an oxidation rate of 2 to 3% per hour was observed suggesting that photo-chemical (gas-phase) processes might play an important role in SO_2 oxidation at this site. It might be added here that, compared to the Suncor power plant plume, such oxidation rates are substantially higher than those suggested for sour gas plant plumes which contain low levels of oxides of nitrogen and hydrocarbons. The 1977 field observations showed no evidence of theoretically predicted temperature and relative humidity dependence that would be expected of liquid-phase chemistry even though the plume contained high levels of particulate matter that could function as effective catalysts.

It has been shown from the determination of rate constants for the major homogeneous oxidation steps for SO_2 under Alberta conditions that the average lifetime of SO_2 is 3.5 days during typical summer conditions and 522 days during winter conditions. Computer simulations employing 88 reactions and 12 air contaminants including SO_2 were carried out. The main prediction was that the sulphur concentration of the aerosols, such as H_2SO_4 and H_2SO_5, would be larger than that of SO_2 roughly 7.5 hours after the start of the calculations (0800 local time) if it was assumed that the reaction

products of SO_2 oxidation contribute to aerosol formation [115]. Field observations are necessary to verify this chemical model.

From the foregoing it is clear that there is a need for research on the chemistry of plumes from different industrial sources. More generally, the chemistry of SO_2 under Alberta winter conditions, such as aqueous-phase oxidation and potential SO_2-ice fog interactions, is poorly known and in need of clarification. It is also clear that atmospheric chemistry should be incorporated into dispersion models used for predicting SO_2 concentrations at the surface from sources such as oil sands plants and power plants which contain particulates and other contaminants. These areas of research have been identified recently [116].

3.3 REMOVAL

Sulphur gases and their oxidation products are removed from the atmosphere by dry and wet deposition mechanisms. Deposition velocities usually are measured 1 or 2 m above ground level. Occasionally, in forests for example, it is difficult to obtain concentration measurements at the standard height. The prediction of gaseous concentrations near the ground in modelling calculations is not straightforward since surface roughness, wind speed, and temperature stratification determine transport toward the surface. Deposition of particles such as sulphates is strongly dependent on particle size. In Alberta, no experimental measurements of SO_2 deposition velocities have been carried out under prevailing meteorological conditions. These measurements are needed to determine precisely the dry deposition rates of sulphur compounds.

Wet deposition of SO_2 and particulate sulphate results from two types of processes: those associated with cloud phenomena (rainout), and those concerned with scavenging by falling precipitation (washout). At the present time it is possible to describe washout processes theoretically, but no adequate theory of rainout exists. Sulphur dioxide and particulate sulphate have a high

solubility in water; their concentration is influenced by the wet removal process. Because of this, these compounds have a profound influence on precipitation chemistry.

Systematic studies of sulphur in precipitation have been underway for the past 10 years in central Alberta where most of the natural gas processing plants are located [117-119]. These investigations were undertaken to explain two observations: 1) a decrease in the sulphur deficiency of soils; and 2) a marked reduction in hail activity in central Alberta since 1961 and a concurrent increase in the number of reports of soft hail. By determining the concentration of SO_4-S in samples of rain and snow collected during summer and winter from 1966 to 1969 and by assuming a regional annual precipitation of 45 to 56 cm, the annual deposition of sulphur in central Alberta was calculated to be 2.2 to 4.4 kg/ha. Moreover, it was concluded that most of the sulphate in rain and hail from central Alberta is of local industrial origin and that snow is a poor scavenger of atmospheric sulphur compounds.

In a more recent study [120], the amount of SO_4-S in rain, hail, snow, and dust fall was determined and the results indicated that the average annual deposition of SO_4-S is 2.2 kg/ha (2 lb/acre). This amount accounts for only 15% of the total yearly industrial sulphur emissions in the area.

Dry and wet deposition rates of various ions were reported for a one-year period in central Alberta. The estimated annual atmospheric deposition of sulphur was 18.6 kg/ha (5589 mg/m^2 SO_4). The ratio of dry to wet deposition was found to be 4.8 [121].

A field study of sulphur in snow was conducted in the Athabasca Oil Sands area near an oil sands plant in February 1976 [122]. The results showed that the maximum annual sulphur deposition in the area is about 3.7 kg/ha (1.0 mg/m^2/day).

Theoretical calculations have indicated that annual sulphur deposition from oil sands plants in the Athabasca region of Alberta may be as high as 32 kg/ha [100]. Other theoretical calculations suggest that deposition could be greater than 4 kg/ha during July

in the vicinity of a large sour gas processing plant [123]. This value is high because only meteorological conditions characterized by trapping atmospheres were considered. A recent modelling study has concluded that the maximum annual gaseous sulphur deposition, in dry and wet form, from a sulphur extraction plant should be less than 10 kg/ha [124]. Deposition velocities from the literature were used to derive dry deposition estimates; wet deposition was calculated employing equilibrium scavenging concepts. The effects of these depositions on water, vegetation, and soils are discussed in following sections.

It is evident that precise estimates of dry and wet deposition, from different sources such as power plants and fertilizer plants and in various regions of Alberta, have not been made. Since the climates of northern and southern Alberta are somewhat different, area and source specific studies should be promoted to assess the removal of sulphur from the atmosphere.

4. EFFECTS IN THE WATER

As indicated earlier, the methods of transport, chemical transformation, and deposition of atmospheric sulphur cannot at present be given precise description. It is apparent that not only may sulphur enter surface and groundwater by many routes, but also the physical, chemical, and biological pathways are virtually unknown by which sulphur is distributed in aquatic ecosystems.

In Alberta, sulphur may enter receiving waters directly from natural sources, from the atmosphere, from agricultural application, from industrial waste water discharges, by seepage from storage ponds, or by loss from solid sulphur storage areas and during transportation.

Limited data for Alberta suggest that sulphur in water likely is not of urgent concern at present, but at the same time requires an organized research effort to provide more reliable data.

One of the problems created by sulphur emissions in many areas of the industrialized world is the formation of acid precipitation which progressively strips the buffering capacity of soils and eventually lowers the pH of surface waters. A recent overview of the potential for acid precipitation from sources in northeastern Alberta has stressed the need to identify sensitive areas downwind, and to take immediate steps for their protection [125].

The pH of precipitation has been monitored at 11 stations located in various regions of the province [126, 127]. Most of the samples exhibited a pH of 6 to 7.5. Some values in the range of 4 to 5 were observed in the vicinity of Edmonton and Calgary, the two major urban centres in Alberta. Low values may also occur as the result of plant upset or breakdown of pollution control equipment at major sulphur producing operations. The addition of sulphur to waters in the province does not appear to be of such a magnitude to cause serious concern. However, a lack of published information

is evident, particularly with respect to low level, but persistent, inputs of sulphur to aquatic ecosystems in Alberta.

The following brief examination of published reports from Alberta provides a preliminary review of sulphur compounds in waste waters and in natural waters, and briefly discusses lake acidification.

4.1 WASTE WATER

Three classes of gas processing plants are categorized by Alberta Environment for waste water management purposes. Class A plants do not recover sulphur; Class B plants do recover sulphur. Neither discharge waste water to the surface waters of the surrounding area. Both A and B plants, however, may dispose of produced or plant waste water by deep well injection. Class C plants may or may not recover sulphur but discharge treated plant waste waters on a continuous basis. The types of wastes and their origin and treatments have been reviewed [128, 129]. Within the gas plant, hydrogen sulphide is the predominant sulphur-containing impurity in the waste water. Generally, these waste streams are treated by biological oxidation and extended aeration, followed by foam fractionation. The effluent remaining after evaporation is usually disposed of by deep well injection at Class A and B plants. At Class C plants, these effluents are treated extensively to meet provincial requirements and continuously discharged to surface waters.

Surface runoff associated with the plant site and sulphur block storage areas may carry significant quantities of sulphur. The production of acidic waters within sulphur storage blocks by moisture and the action of micro-organisms in the soil results in drainage waters of low pH and high metal content [130]. With caustic treatment in ponds, the metals precipitate out and form a sludge. The remaining meutralized effluent may be injected into deep wells or discharged into surface waters, provided it meets the required standards.

In summary, waste waters associated with gas plants do not appear to cause widespread environmental effects. Class A and B plants strive for zero discharge with the occassional release of treated waters. Class C plants with continuous discharge use extensive treatment procedures. However, low winter temperatures may reduce the efficiency of the treatment processes.

Because of the nature of extraction methods presently used in oil sands plants, waste water containing clay tailings and other chemicals is stored in large ponds. Data in existence in the open literature or in unclassified company reports on the physical, chemical, and biological characteristics of clay tailings have been reviewed [131, 132]. Organic sulphur compounds associated with the Suncor extraction plant were analyzed. The natural background levels of the intake waters were 0.1 to 0.4 mg/L. Increasing concentrations were detected from the upgrading plant waste waters (2.1 to 2.9 mg/L) to the dike drainage waste waters (3.0 to 5.4 mg/L). Although a number of compounds in the molecular weight range of 148 to 262 were identified, a large number remained unidentified [133, 134].

4.2 SULPHUR COMPOUNDS

Naturally occurring organic sulphur compounds are found in soils and surface waters of Alberta. In general, river and lake waters contain only elemental sulphur and high molecular weight organic compounds of sulphur. However, surface waters near gas plants tend to contain increased numbers and increased concentrations of these compounds, some of which may be industrially generated [135]. With increased concentrations, the natural reactions between elemental sulphur and organic matter increase, and increased populations of specifically adapted micro-organisms have been identified [136].

In a hydrogeochemical study of the surface waters in the Mackenzie River basin, including several rivers and lakes in Alberta, the fractionation by microbial activity was not great enough to totally mask the geological sources of the materials. Preliminary

results indicate either pyrite, discharging formations, or gypsum to be the major source of sulphur compounds. Further detailed study is required to reveal their relative importance [137].

4.3 ACIDIFICATION OF WATERS

In the spring of 1945, an attempt was made to acidify (to pH 5.0) a portion of Baptiste Lake near the town of Athabasca, Alberta to eliminate a fish parasite [138]. The volume of water in the spawning bays was estimated to be a strip of water 13 km (8 miles) long by 6 m (20 feet) wide with an average depth of 1 m (3 feet). Based on the measured alkalinity of the water at 175 ppm (203 mg/m^3 HCO_3), the quantity of commercial grade sulphuric acid necessary to neutralize this alkalinity was calculated to be 13.1 t (14.4 tons). On addition of the acid, the lake water pH dropped below the range of the indicator (5.0); however, within a half hour or less the upper waters had returned to their normal pH (8.0). Very acidic conditions existed in the bottom mud for several hours but by the next day they had returned to their normal pH. A total of 18 t (20 tons) of sulphuric acid had failed to increase the acidity for more than a few hours. It was suggested that the carbonate buffers completely neutralized the acid.

This hypothesis is supported by the only other lake acidification research done in Alberta [139]. This study in the Athabasca Oil Sands area concluded that the sensitivity of lakes to acid loading is dependent on the amount of carbonaceous material in the lake and that for this area even the most poorly buffered lakes sampled will be seriously affected only if the pH of rain averages below 4.0. Because of the generally high alkalinities and the presence of carbonate materials in soils throughout most of the area, it is unlikely that any significant alteration of pH in lakes of the study area will occur, given the projected levels of sulphur emissions from surface mining extraction plants.

Buffering capacity is defined as the ability to resist change as a result of acid input. This buffering capacity is related

directly to the types of soils in the drainage basin, the ratio of water to land area in the basin, and the types of sediments and solutes carried into the lake. The neutralization of strong acids from precipitation is largely accomplished (about 75%) in the soil zone by the rapid reaction with bases and biological matter. The acidification potential of soils and their distribution in Alberta have been discussed recently [140]. Highly calcareous soils have been identified as the most resistant and acidic sandy soils the most sensitive. Lakes or streams associated with each soil type will be similarly influenced.

5. EFFECTS ON SOIL AND VEGETATION

The most controversial question about industrial sulphur emissions in Alberta is whether the sulphur emissions are having an effect on the vegetation and soils. News of the severe effects which have occurred in eastern Canada and the United States has been sufficient to cause concern in the Alberta public and scientific communities, even though the sulphur loadings in Alberta are evidently much lower than those in eastern Canada and the U.S. Because the sulphur loadings are lower in Alberta, no severe effects are expected in the province. However, there is not sufficient scientific evidence either to substantiate or refute the possibility that cumulative subtle effects of sulphur emissions may result in long-term reduction in soil and vegetation productivity. These same long-term cumulative effects may disrupt the dynamic stability of native ecosystems.

5.1 FORMS AND MODE OF DEPOSITION

Studies in Alberta have indicated that deposition of sulphur occurs by means of scavenging by precipitation (including snowfall), deposition of particulates (elemental sulphur and salts of sulphur), and direct sorption of gas by soil [141-150]. There is, however, disagreement in the literature from Alberta concerning the relative importance of each form in depositing the majority of the sulphur. This disagreement is a direct result of methodology used in measuring deposition, as well as time and place of measurement, and environmental conditions (weather and vegetation cover in particular).

One study [141] indicated that accumulated SO_4-S in the snowpack at 5 km from the source was less than 1 kg/ha and only slightly greater than at a distance of 450 km. Concentration in rain was five times the concentration in snow at remote and near stations. Rain intercepted by forest trees, however, contained monthly concentrations of SO_4-S of 0.2 kg/ha at the remote stations as opposed to 2.6 kg/ha at stations near to the emission source. It was not known

what percentage of sulphur was deposited as H_2SO_4 as opposed to neutral salts. However, it was stated that precipitation in Alberta is seldom highly acidic. These results confirm the greater concentration of sulphur in intercepted rainfall noted in earlier studies [144, 151]. The amount of sulphur deposited in precipitation was less than that absorbed by vegetation and soil. Very little sulphur was deposited on snow as particulates or by direct absorption. Sulphur dioxide deposited by precipitation was reported as about one tenth that deposited directly on the soil or absorbed by surface water or vegetation [144, 152].

There is evidence of differential uptake of SO_2 by wet and dry soils, with wet soils apparently absorbing greater quantities [142]. European studies have indicated that atmospheric humidity also affects absorption.

5.2 SOIL AND VEGETATION IN RELATION TO EMISSION SOURCES

5.2.1 Natural Soils Conditions

The variety of soils in Alberta poses extreme difficulties in assessing the potential effects of sulphur deposition in the province. Total sulphur in surface soils increases from brown through dark brown to black chernozemic then decreases in dark grey and grey luvisolic soils [153]. Sulphur-deficient soils have been reported for much of northern Alberta and include a number of soil series of the grey luvisolic order [154-156]. The Alberta Institute of Agrologists [157] specifies S deficiency as 5.6 kg/ha (5 lb/acre). Increased heavy applications of N fertilizer increase the frequency of S deficiency in cereal grains, not only on grey luvisolic soils but also on dark grey and black chernozemic soils [154]. Low intensity sampling indicated a deficiency in 7 to 14% of dark brown soil zones and in 21 to 32% of grey luvisolic soils [158]. In 1972, 50% of the currently cultivated plus potentially arable land in the province lay in the grey luvisolic soil zone; the zone contained about 15% of Alberta's cultivated land at that time [157].

While the above discussion was based on papers which emphasized the occurrence of sulphur-deficient soils in Alberta, the importance of that phenomenon as related to sulphur impingement is clouded by the occurrence of natural acidity directly associated with those soils. The grey luvisolic soils are often acidic (approximately 31% with pH < 6.0 in the Peace region), and the Ap horizon over solonetzic subsoils may be acidic [157, 159]. Because of the timing of deposition, atmospheric sulphur will not necessarily alleviate sulphur deficiencies. In 1971 it was reported that sulphur oxides in the atmosphere in central Alberta were not contributing sufficient sulphur to eliminate the deficiency except where the deficiency was marginal [160]. Where sulphur impacts on already acidic soils, the potential exists for detrimental effects on soil chemistry and soil nutrient status.

5.2.2 Location of Emission Sources in Relation to Soils

The location of sulphur emission sources is presented in Figure 1. If superimposed over a soils map of Alberta (Figure 4), and if one considers the prevailing wind direction, it would be seen that these sources lie in, or closely upwind of, the grey luvisolic soils zone or the solonetzic soil zone. However, generalities should not be made regarding the potential of these sources to reduce soil productivity. A study is currently underway to develop methodology for mapping sensitivity of soils to sulphur impingement [140].

5.2.3 Vegetation Associated with Sulphur Emission Sources

Sour gas or oil sands plants in Alberta are located in the major forest vegetation zones occurring in the province [i.e., boreal mixed-wood and coniferous (spruce or pine) forests, subalpine spruce-fir forests and aspen parklands] as well as in agricultural cereal croplands and grasslands. Effects of sulphur emissions have been reported and experimental studies carried out in most, if not all, vegetation zones.

N
MEDICINE HAT

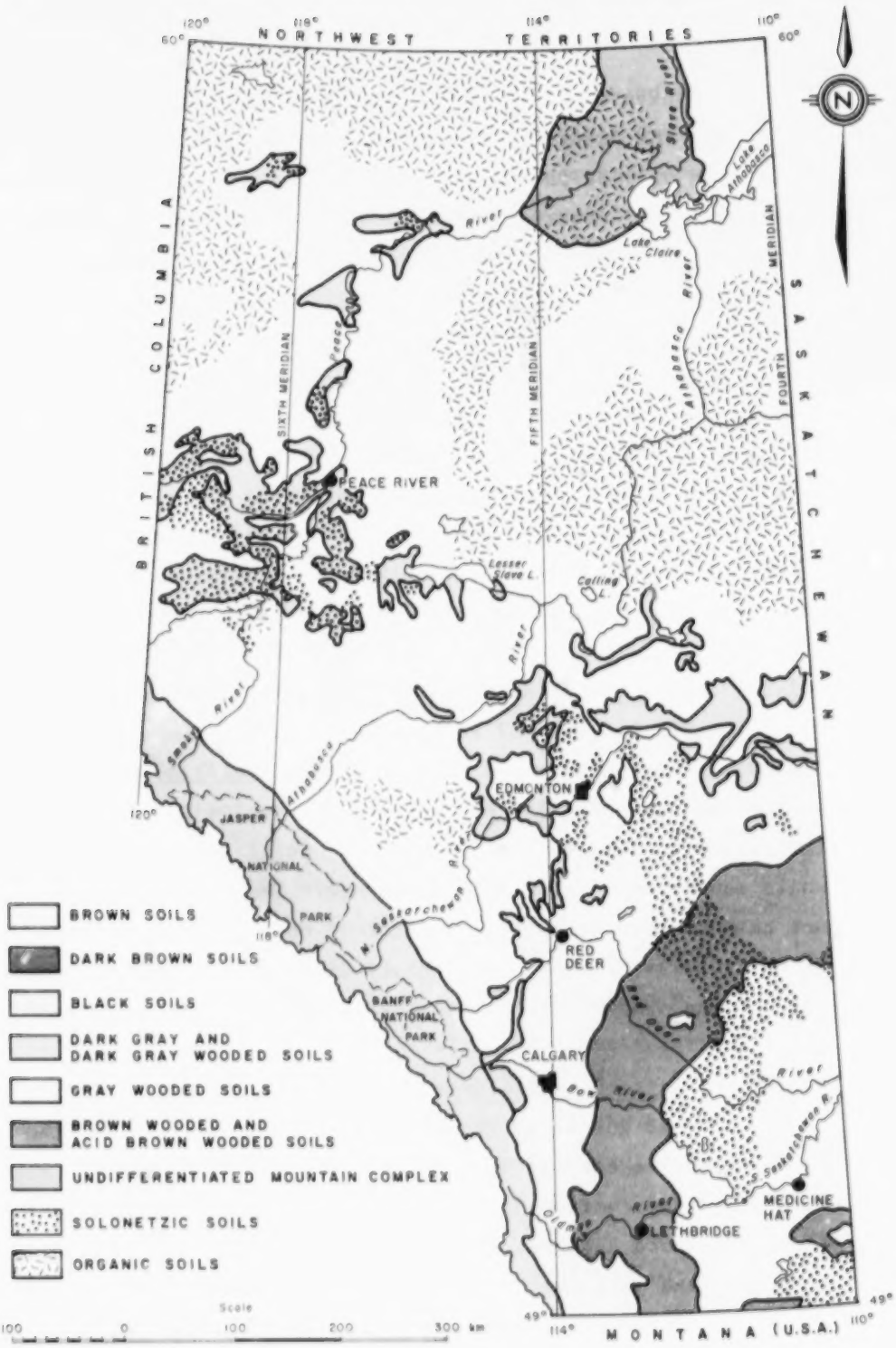

FIGURE 4. SOIL GROUPS OF ALBERTA

5.3 METHODS OF ASSESSING UPTAKE OF AIRBORNE SULPHUR BY SOILS

Methodology has included measurements of total sulphur, sulphate sulphur, isotopic sulphur, and pH in soil samples [141, 144, 145, 152, 161-163]. Potted soils have been exposed in the wet and dry state and under both sheltered and open situations, the latter in an effort to differentiate between gaseous absorption and deposition in particulate form and by precipitation [141, 144, 145, 152]. Agricultural soils have been used in forested zones in some of these experiments and soils have sometimes been covered with organic matter, mosses, lichens, or other vegetation [144, 149, 152, 164]. Probable sulphur uptake by soils has been interpreted from uptake by vegetation, precipitation, and particulate sampling, and from sulphation cylinder and lead candle readings.

There have been differences in the interpretation of data from similar areas and poor comparability among studies resulting in inconclusive evidence of the ultimate long-term effects of sulphur deposition on Alberta soils.

5.4 EFFECTS OF SULPHUR ON SOIL CHEMISTRY AND NUTRIENT STATUS

The majority of world literature indicates that sulphur dioxide tends to acidify soil when deposited in substantial amounts over extended time periods [149]. Several studies have concluded that the same process is occurring in Alberta, although the rate of deposition is variable and the amounts of SO_2 deposited are much less than those deposited in eastern Canada, eastern United States, and some European countries [141, 144, 145, 149].

A decrease in soil pH of 0.15 units in a three-month period was reported over a 1000 km^2 area in southern Alberta and over a 25 000 km^2 area in central Alberta [141]. The same study utilized agricultural soils under canopies downwind of sources representing 50% of the sulphur emissions in Alberta at that time. Reference to unpublished results of other studies in forested areas indicated pH reduction in mineral soil of 0.05 to 0.10 units over 3 to 10 months and an apparent pH reduction in surface organic matter of 1 to 2 units up to 26 km (16 miles) from the sulphur emission source after

15 years [152]. Similar results have been reported for agricultural areas [165]. Other studies generally support the conclusion that soil pH has been lowered downwind of sulphur emitting sources [144, 145, 151, 163, 166].

Despite these results, the picture is by no means clear. One study indicated that there was no change in pH of potted soils while undisturbed soils (grey luvisolic) decreased 0.1 pH units [150]. Other studies have concluded that there is not enough evidence to attribute soil acidification to industrial sulphur emissions [167, 168]. As well, pH of soils normally ranges widely over time and space, at least as much as differences attributed to sulphur emissions, creating difficulties in comparing exposed and unexposed sites [141, 150, 165].

Generally, studies relating to effects of sulphur emissions on soils in Alberta have not been detailed sufficiently to provide sophisticated information on changes in soil chemistry or to relate changes in soil chemistry to specific sources of sulphur. The literature does not indicate a clear trend of electrical conductivity, total sulphur, or pH with distance from source [141, 169, 170]. Soil pH usually is not expected to be correlated with total sulphur or water extractable sulphates, two parameters which have been used to indicate impacts from emission sources [169, 170]. One study indicated a greater relationship between KCl extractable aluminum and acidity than between pH and acidity; pH alone was not a reliable parameter for describing changes in soil acidity [151]. Where acidification of soils has occurred there is generally an increase in the availability of manganese, aluminum, sulphur, phosphorus, and potassium, and a concurrent decrease in the availability of calcium, magnesium, and iron [143, 151, 171, 172].

While catastrophic impacts are not present, or expected, on a large scale in Alberta, local effects of windblown sulphur from stockpiles can be severe. Present evidence indicates that these local areas can be reclaimed successfully by liming [173, 174]. Less information is available on the effects on soil water of leachate or windblown sulphur from sulphur storage piles [130].

5.5 METHODS OF ASSESSING SULPHUR EFFECTS ON VEGETATION

Other than surveys of visual symptoms of sulphur damage to vegetation, or total disappearance of species, no large body of literature exists on experimental methods for assessing sulphur damage to vegetation in Alberta. Sophisticated experimentation required for this research is expensive and time consuming and only two centres in the province, with limited resources for research, have addressed the problem. Nevertheless, research from these centres has confirmed the findings from other regions, and broadened them to include native vegetation, especially pine.

At one laboratory, scientists have concentrated on carefully controlled laboratory growth chamber exposure of plants to sulphur dioxide, and on treatment of plants with aqueous solution of sulphur dioxide to obtain baseline responses for planned comparison with field samples. Both examination of cellular constituents by electron microscopy and careful analysis of biochemical reactions have been carried out [175-177].

At the other research centre, extensive efforts have been made to evaluate photosynthetic efficiency using portable chambers under field conditions as well as to simulate field growth conditions for laboratory growth chamber tests. In addition to net photosynthesis, nutrient balance and a variety of biochemical reactions have been examined [143].

Considerable developmental work remains to be done before fully suitable methods will be available for analysis of the amount, form, and physiological activity of sulphur found in vegetation in the field.

5.6 EFFECTS OF SULPHUR ON VEGETATION

5.6.1 Agricultural Crops

Sulphur is an essential nutrient in plants and, as pointed out above, there are considerable areas of soil in Alberta with a significant deficiency. Based on spring soil sampling, fertilization

of these areas in proper combination of nitrogen and sulphur can result in a significant increase in yield of field crops [156, 178]. However, the impact of sulphur from emission sources cannot be relied on to provide sulphur fertilization to deficient soils because of the variability in forms, amounts, and timing of deposition [160, 179]. In contrast, many of the soils in Alberta are very high in sulphur content; on these soils, luxury consumption of sulphur is well documented with no apparent ill effects [160, 178]. In agronomic crops, the excess sulphur accumulated as sulphate in the straw [178].

The potential effect of sulphur emissions on agricultural crops seldom is reflected directly in crop damage but more often indirectly through effects on soil acidity. Acidity is a significant factor in affecting the productivity of cereal and range crops. Pot studies at pH 5.0 indicated that tolerance of some crops to acidity was as follows: oats > rape = barley >> alfalfa. Under field conditions: red clover > rape = Olli barley > Galt barley > alfalfa. A decrease of 1 pH unit means that many Alberta soils could not grow alfalfa and on some soils barley yields would be reduced. In the range pH 5.2 to 5.5, a drop of 0.1 pH unit reduced the barley yield 161 kg/ha (3 bu/acre); in the range pH 5.5 to 6.0, a similar pH decrease reduced alfalfa 448 kg/ha (400 lb/acre) [152, 179-181]. Sulphur requirements of most legumes growing in Alberta are very small. Nodulation of alfalfa was reduced by soil acidity below pH 5.6 and nodulation of red clover was reduced below pH 5.0 [181].

While none of these studies was related directly to impingement from sulphur emissions, they do indicate the sensitivity of Alberta agricultural crops and soils to acidification levels which some researchers claim could result from emissions in the province.

Selenium deficiency diseases are limited in Alberta to the eastern foothills region from Whitecourt to Pincher Creek [164]. Sulphur in feed can aggrevate Se deficiency by interfering with

metabolism of rumen bacteria. Competition between sulphur and selenium suppresses the uptake of selenium by vegetation and, at low pH, selenium may form unavailable complexes with heavy metals [164, 182, 183]. One study suggested that sulphur decreased selenium concentration only if growth were enhanced. As forage yield was increased by sulphur fertilization, constant selenium uptake decreased selenium concentration. No correlation was found between soil pH, water soluble soil sulphates, total plant sulphur or plant protein content, and selenium concentration [160]. No clear examples of airborne sulphur contributing to selenium deficiency have been found.

5.6.2 Forest Vegetation

There have been two approaches by scientists working on the question of sulphur dioxide effects on forest vegetation. One school gives major attention to visible symptoms while the other is more concerned with what may be called previsual symptoms.

The visible symptoms are frequently subdivided into acute, chronic, and transient symptoms depending on the severity and duration of the effect [141, 143, 147, 169, 184-188]. Transient refers to symptoms which are transitory on foliage during the growing season. No visible damage to cells occurs and on conifers the current year's growth is healthy. Chronic refers to symptoms which persist until foliage abscises. Damage to cells is visible but on conifers current growth is healthy. Acute refers to killing of tissue of coniferous and deciduous species followed quickly by abscission. All needles can be affected on conifers. It is not certain if permanent physiological damage occurs in the vegetation which has suffered severely enough to have exhibited visible symptoms, but changes in the competitive relationships would indicate some persistent effect [184, 186, 187]. A problem affecting interpretation of symptomology is that symptom development is dependent on environmental conditions, and the pollutant is seldom pure or in a steady dose similar to the usual laboratory conditions

under which symptomology has been developed [143, 148, 187, 189, 190]. Sensitivity of some Alberta species has been ranked in Table 4 [169]. Another study (visible symptoms) on native species, using CO_2 gas exchange, rated paper birch (*Betula papyrifera* Marsh) most sensitive to SO_2, followed by green alder [*Alnus crispa* (Ait.) Pursh], jack pine (*Pinus banksiana* Lamb.), Labrador tea (*Ledum groenlandicum* Oeder), and white [*Picea glauca* (Moench) Voss] and black spruce [*P. mariana* (Mill.) B.S.P.] [191]. The results of additional work on the same project are shown in Table 5 for visible effects and Table 6 for net assimilation rate. The results shown demonstrate the variability of both visible and previsual symptom thresholds in native species [192]. It should be noted that foliar sensitivity is not synonymous with overall resistance or ability to recover from injury.

Careful examination of plant tissues when exposed to very low concentrations of SO_2 in the laboratory has resulted in a clearer understanding of the mode of activity of SO_2 and has disclosed possibilities for environmental damage undetectable by immediate visual symptoms [143, 175-177, 187, 190, 193]. Work with combinations of SO_2 and NO_2, as well as SO_2 and metals such as vanadium and nickel, indicates potential additive or synergistic (greater than additive) metabolic effects [194, 195]. Previsual symptoms at the ultrastructural and biochemical level support the visible evidence that response to SO_2 fumigation increases with the physiological age of tissue [175, 190]. Previsual physiological disruption occurs primarily in connection with photosynthetic processes, and ranges from organelle swelling and membrane disruption [175, 193], through changes in biochemical balances [143, 176, 177, 190, 195] to adenosine triphosphate (ATP) shortages [143, 177, 187, 190]. Although these symptoms usually are thought to be reversible by removal of SO_2 stress, there is some evidence of persistence resulting in net growth reduction [177]. It is important to note that the main functions which are disrupted by SO_2 stress are involved in photosynthesis [143, 175-177, 187, 190, 193].

Table 4. Sensitivity of some Alberta plant species to fumigation by SO_2.[a]

Trees		
Most Sensitive: (to foliar injury)	Balsam Poplar	*Populus balsamifera* L.
	Alder	*Alnus tenuifolia* Nutt.
	Trembling Aspen	*Populus tremuloides* Michx.
	White Birch	*Betula papyrifera* Marsh
	Willow	*Salix* spp.
Least Sensitive: (to foliar injury)	White Spruce	*Picea glauca* (Moench) Voss
Scrubs		
Most Sensitive:	Wild Raspberry	*Rubus strigosus* Michx.
	Wild Gooseberry	*Ribes lacustre* (Pers.) Poir.
	Wild Rose	*Rosa acicularis* Lindl.
	Honeysuckle	*Lonicera involucrata* (Richards.) Banks
	Dogwood	*Cornus stolonifera* Michx.
	Saskatoon	*Amelanchier alnifolia* Nutt.
	Low Bush Cranberry	*Viburnum edule* (Michx.) Raf.
	Bog Birch	*Betula pumila* L. var. *glandulifera* Regel
	Wolf Willow	*Elaeagnus commutata* Bernh.
Least Sensitive:	Bear Berry	*Arctostaphylos uva-ursi* (L.) Spreng.
Herbs		
Most Sensitive:	Fireweed	*Epilobium angustifolium* L.
	Sweet Coltsfoot	*Petasites palmatus* (Ait.) A. Gray
	Bunchberry	*Cornus canadensis* L.
	Wild Strawberry	*Fragaria virginiana* Dcne.
	Arnica	*Arnica mollis* Hook.
Least Sensitive:	Wild Aster	*Aster ciliolatus* Lindl.

[a]Hocking [169].

Table 5. Time (mean ± 95% confidence limits) required for visual symptom development during fumigation with 0.34 ppm SO_2.[a]

SPECIES	TIME (DAYS)	
Willow	1.7 ± 1.4[b]	[b]
Green Alder	3.2 ± 1.4	
Aspen	4.3 ± 1.3	
Paper Birch	4.5 ± 1.7	
Labrador Tea	8.5 ± 2.8	
Jack Pine	10.6 ± 2.4	
Black Spruce	15.2 ± 5.4	
White Spruce	21.3 ± 4.0	

[a] Addison and Malhotra [192].

[b] Means that are joined by a vertical line are not significantly ($p < 0.05$) different in a Student-Newman-Keuls test.

Table 6. Slope (regression coefficient) of the change in net CO_2 assimilation rate (NAR) with time during fumigation with 0.34 ppm SO_2. Negative signs indicate a reduction in NAR with time. Units are percentage of maximum NAR decrease per day.[a]

SPECIES	PREFUMIGATION SLOPE	FUMIGATION SLOPE
Willow	-1.09	-9.91[b]
Paper Birch	+1.70	-8.69[b]
Aspen	+2.13	-7.68[b]
Green Alder	+0.19	-4.29[b]
Labrador Tea	-3.18	-2.15[b]
White Spruce	+0.01	-2.06[b]
Black Spruce	+0.48	-1.69[b]
Jack Pine	+1.51[b]	-1.30[b]

[a] Addison and Malhotra [192].

[b] Slope is significantly ($p < 0.05$) different from zero.

[c] Vertical lines join slopes that are not significantly ($p < 0.05$) different by the Simultaneous Test Procedure.

The epiphytic lichens and bryophytes are the two forms of vegetation considered to be most sensitive to air pollutants, including sulphur compounds [146, 148, 196-200]. There is solid evidence from stable sulphur isotope analysis that the sulphur given off by a refinery may be found in mosses [186]. In Alberta, species have been found that respond to different levels of air pollutant; therefore, it is possible in many localities to develop a map of pollution concentration using a combination of lichen species and their relative densities [187, 193, 196, 198]. Such networks have been established, but re-evaluations for most of them have yet to be published [196, 199]. The results from one published study were inconclusive [201]. Existing field studies have indicated that lichens are more sensitive to air pollution than laboratory experience would lead one to expect [197]. This could be the result of synergistic effects by multiple pollutants, or differences in response because of environmental conditions.

The factor which makes the epiphytes so susceptible to air pollution is their occupation of a niche dependent on airborne rather than soil-borne material. This same niche specialization makes them a valuable sampling tool in a monitoring program since they avoid the complication of indirect soil effects [143, 186, 196, 197, 202].

Species in a community vary in their tolerance for SO_2, causing some species to die out earlier and making it possible for a species to show an initial increase in dominance as competition is reduced, followed by a decline as pollution continues [164, 186, 198, 200, 202, 203]. One study which analyzed both vascular plants and epiphytes found that both responded with altered competitive behaviour [186]. In this study, as in others, the presence of a vegetative cover apparently reduced the direct accumulation of sulphur in the soil [143, 186, 194]. Data are completely inadequate, however, to predict either sequences or rates of population structural changes, or changes in physiological condition for any plant species in Alberta.

One of the points of chief concern among plant ecologists has been the potential for reduction in net productivity in the absence of visible evidence of tissue damage [143, 147, 204]. Direct evidence of such growth reduction has now been obtained in both field and laboratory experiments on higher plants [143, 204].

Physiological evidence indicated that lodgepole x jack pine hybrids exposed to SO_2 in the field initiated photosynthesis later in the spring than did unexposed trees on comparable sites [143]. In addition, the exposed trees had a maximum photosynthetic rate which was less than that of unexposed trees. Among the most important points to be elucidated in this study was that a statistically significant decrease in basal area increment could be correlated with SO_2 emissions when site differences were taken into account. This study also indicated that the best time to evaluate foliar nutrients and physiological processes was at the end of the growing season, because the exposed and unexposed foliage were in a more similar phenological status than earlier in the growing season [143].

Stable isotope ratios ($^{34}S/^{32}S$, see Section 7) of trees examined throughout the growing season indicated that sulphur during early growth stages was taken preferentially from the soil while, in later growth stages, proportionally greater amounts of sulphur were taken from the air. Because the soil has a lower $^{34}S/^{32}S$ ratio than that of air, the situation resulted in a low concentration of the stable heavy sulphur isotope (^{34}S) in the foliage during the early part of the growing season. As summer progressed, the ratio of $^{34}S/^{32}S$ (and level of ^{34}S) in the foliage increased and, in some instances, exceeded the value in the ambient air [143].

In addition to trees exhibiting a surplus of nutrients, including phosphorus, as a result of excessive sulphur, some instances of apparent phosphorus deficiency also have been noted in the field [143]. However, this may have been the result of a natural deficiency of phosphorus in the soil, as other studies

have found an apparent mobilization of phosphorus resulting from sulphur additions [151, 171, 172]. Phosphorus availability is pH dependent and therefore the effect of sulphur would be dependent on the original soil condition. Metabolically, the deficiency of phosphorus in vegetation at the Windfall gas plant appeared to be expressed in a suboptimal content of ATP in the foliage (see Figure 5) [143, 189].

5.7 ECOSYSTEM EFFECTS

Studies in Alberta to date have been concerned with effects on plant parts, individual plant species, and specific soil parameters. Very few researchers have considered the total ecosystem [143, 167] and none has dealt with it experimentally. The assimulative capacities of ecosystems have not been tested in Alberta, although it has been suggested that leaching and buffering by plants and soil microflora have been underestimated in reducing the effects of SO_2 on ecosystems [167].

In forest ecosystems, complex effects of the vegetative cover and extent of the buffering capacity are not well understood. Throughfall pH is positively correlated with pH of general rain but this is not so with stemflow. Therefore it has been suggested that the low pH of stemflow may be related to tree bark (and thus tree species) as much or more than to adsorbed SO_2. As well, pH of throughfall and of general rain increases during the season. This is not so with stemflow, reinforcing the argument for the effect of bark [151, 205].

Soil texture and chemistry confound the effects of sulphur deposition. More SO_2 is absorbed by fine-textured soils and by wet soils [144]. As well, injury to plants by SO_2 is greater when relative humidity is high and available nitrogen is low [183]. Other environmental factors affecting plant tolerance to SO_2 include: (1) light intensity before and during fumigation; (2) temperature; (3) water on leaves; (4) maturity of plants or plant parts; (5) vigor of plants; and (6) genetic factors [148, 189].

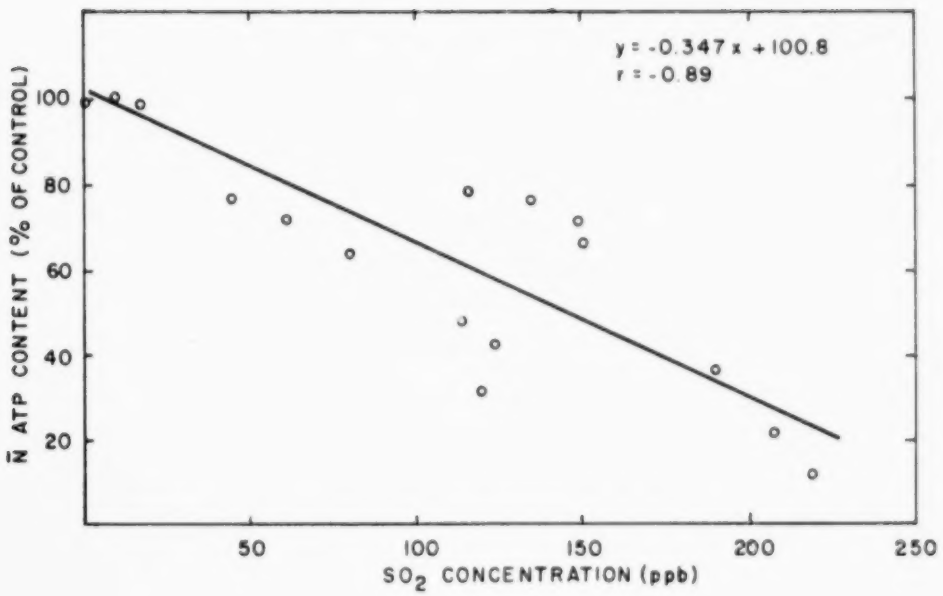

Figure 5. A scatter diagram of the normalized content of ATP in lodgepole-jack pine needles plotted against the instantaneous sulphur dioxide concentration of the ambient air. The equation of least means linear fit and the coefficient of correlation are shown in the upper right-hand corner. The regression coefficient is significant to the 1% level. Values are for foliage stabilized during sulphur dioxide fumigations of industrial origin [189].

Sulphur may enter plants as sulphur dioxide through the stomates or as sulphate through the soil [177]; the subsequent metabolic pathways are different. The route of absorption through the soil is far more complex and creates more widespread changes in total soil chemistry involving the availability of other essential or toxic elements than does the direct route. However, it has been stated that sulphur gas emissions are affecting the ecosystem both directly and indirectly by adversely modifying foliar nutrient status and hence nutrient cycling. The physiological mobility of essential and toxic nutrients within the plant may be affected. Evidence of preferential *in vivo* biochemical fractionation of sulphur isotopes in tissues, as well as of chemical extraction fractionations, indicates the need for physiological and biochemical studies to support understanding of material movement and cyclic processes throughout the ecosystem. Sulphur, nutrient, toxicant, and heavy metal evaluations should be done concurrently on ecologically comparable sites to allow some meaningful analysis of ecosystem loading and of distributional pathways and processes [143].

Agricultural systems are less complex than forest systems and much better understood. Buffering by vegetation is not a major factor. Nevertheless, aspects of soil chemistry and nutrient uptake by crop species and buffering capacity of different soil types in Alberta have not yet been thoroughly investigated [140].

Only one representative of consumer biota, moose (*Alces alces*), has been studied. However, population parameters were studied over a short time scale only. Thus our knowledge of ecosystem impacts is truncated effectively in the producers, with no adequate scientific consideration having been given the consumers and decomposers [206].

If sulphur loading does in fact cause major changes in soil chemistry with concomitant above-normal mobilization of ions (such as heavy metals and salts) in the system, there may well be release of such ions through groundwater and surface water into free

water bodies. This appears to be the likely route by which, over several decades, lakes and streams of northeastern U.S., eastern Canada, and Scandinavia have been seriously affected. It would be an error to conclude that a significant sulphur pollution problem exists now in Alberta, but evidence does exist that there are effects of sulphur on soils and vegetation. A number of knowledge gaps have been identified; this situation can be corrected only by additional research on the general problem.

While changes in individual plant species and soil parameters have been used with some success in monitoring networks, very little is known about how these changes are reflected in the response of the total ecosystem. In order for an organism or a process to be functionally valuable in predicting the changes which can be expected from the ecosystem as a dynamic whole, the functional role of the organism or process must be understood. Therefore, there is a need for emphasis on processes in ecosystem research.

6. EFFECTS ON HEALTH

Relatively few studies from Alberta have addressed the question of potential adverse health effects resulting from exposure to sulphur gases or other air pollutants. Available reports are examined in the following sections.

6.1 NON-LABORATORY SITUATIONS

6.1.1 Human Subjects

The health effects of air pollutants have been assessed on a sample population selected from 13 industrial and nonindustrial urban areas of Alberta. Respiratory function was used as an index of the health status of the population. Although 98.8% of the respondents felt that air pollution was harmful to one's health and 25% of respondents indicated that their own health had been affected, pulmonary function could not be correlated to levels of air pollution in the areas surveyed. A great deal of adverse public opinion existed regarding air pollution, but the respondents' perception of the seriousness of air pollution did not correlate with the measured levels of pollution in their areas [207].

More detailed analyses of potential community health effects arising from kraft (sulphate) pulp mill emissions in Alberta and elsewhere have been reviewed [208]. The main conclusion of this report was that, while odour and nuisance value may be significant, there is no direct correlation between specific cases of physical ill health and pulp mill emissions. It is acknowledged, however, that higher concentrations of the components of pulp mill emissions undoubtedly do have the potential to cause adverse health effects.

Epidemiological studies (pertaining to the incidence, distribution, and control of disease) concerning sulphur oxides have been evaluated [209]. The report questioned the validity of

most epidemiological investigations of sulphur oxides and concluded that no evidence exists to incriminate sulphur oxides in the environment as a health hazard.

Data from clinical exposure studies, conversely, leave no doubt that SO_2 can cause adverse health effects. Generally, studies on humans have been limited to the examination of short-term exposures [209, 210]. In concentrations of 0.3 to 1 ppm, SO_2 can be detected by taste, 4 to 6 ppm results in dryness of the throat and nasal passages, and 5 to 10 ppm can produce bronchospasm in susceptible individuals. These levels of SO_2 are high relative to background levels encountered in the Alberta environment (usually less than 0.001 ppm). Synergism between SO_2 and other potential pollutants (dust or ozone) has been reported but not substantiated [209]. Possible synergistic interactions among pollutants, however, should not be dismissed.

The literature on H_2S has been compiled [211] and reviewed [210]. Hydrogen sulphide may present a more serious health hazard than sulphur dioxide at equivalent concentrations. Nuisance value is significant at concentrations greater than 0.3 ppm.

Data an occupational exposures to toxic concentrations of H_2S have been analyzed [212]. There were 221 cases of H_2S poisoning in Alberta in a five-year period (1969 to 1973) with a mortality of 6%. This number indicated an annual incidence rate of one exposure per 400 workers, indicating a significant health hazard. Also, the medical management of acute H_2S exposure problems was discussed and the report doubted if the administration of an antidote (e.g., nitrite) will offer any significant improvement beyond adequate supportive measures. However, this remains a very controversial area.

6.1.2 Domestic Animals and Wildlife

Effects of air pollution on the health of animals are also of widespread interest and concern, particularly to the farming community whose livestock may be exposed continually to emissions

(mainly SO_2) from nearby gas plants. Adverse effects conceivably could be due to either a direct effect of SO_2 on the animal or an indirect effect mediated by an external factor, such as changes in the constituents of the animal's diet.

Direct, long-term (1 to 3 years) effects of SO_2 emissions from the Waterton gas plant have been studied on cattle, hogs, and chickens [213]. Groups of animals were maintained under natural farm conditions in both emission zones (high concentrations of sulphur compounds) and control zones (low, but not necessarily zero sulphur adsorption). There were no differences in the general health of the animals studied. Thus, despite a firm belief by the agricultural community that SO_2 emissions were adversely affecting the health and productivity of their livestock, no adverse effects were proven.

Direct adverse effects arising from the acute exposure of young (less than 7 days) pigs have been documented [214]. It was demonstrated that a single eight-hour exposure to 5 to 50 ppm SO_2 was associated with reversible eye irritation, nasal secretion, salivation, and altered respiration. Postmortem examination 158 days following exposure showed pulmonary fibrosis which was attributed to higher concentrations of the gas (20 to 40 ppm) [214]. Again, it must be conceded that the concentrations required to produce measurable effects on acute exposure are much greater than those occurring in the environment.

It is widely recognized that sulphur can reduce selenium levels in forage plants and may contribute to a selenium-deficient diet [215]. Further, an excessive consumptions by animals of sulphur (which is also an essential constituent of the diet) may aggravate selenium deficiency by increasing the excretion of selenium in the urine [216]. Deficiency of selenium may cause a group of diseases, commonly called White Muscle Disease (WMD), which may affect cattle, sheep, swine, horses, chickens, and turkeys. Many farmers and veterinarians believe that there may be a correlation between gas plant emissions and the increased evidence of WMD.

However, another source of sulphur results from the application of sulphate fertilizers, the use of which increased over the same period. At present, it is not possible to determine the dominant cause of selenium deficiency diseases. Selenium supplements remain the most effective method for the prevention and treatment [216]. Sampling of 13 sulphur gas plants in west-central Alberta has indicated that the selenium content of stack gases is too low ($1.65\ \mu g/m^3$) to have a toxic effect on livestock [217]. Selenium emitted by the gas plants may be slightly beneficial to livestock near the gas plants, but the overall benefit is negligible.

An important source of H_2S exposure for domestic animals, and a serious occupational hazard for agricultural workers, is so-called "manure gas poisoning". An excellent review on this subject has been published recently [218].

Manure gas consists of a complex mixture of gases which are produced by anaerobic degradation of livestock feces and urine in liquid waste handling systems and which evolve from the slurry, particularly during periods of agitation. Most of the effects of manure gas poisoning have been attributed to hydrogen sulphide in combination with ammonia, methane, carbon dioxide, and a group of more complex but low-level gases. Levels of nil to a few parts per million H_2S in unagitated systems rapidly rise to several hundred or even 1000 ppm during agitation. The effects of such high levels of H_2S, particularly on the cytochrome oxidase system, have been well documented. What are less clear are the effects of prolonged exposure to low levels of H_2S, such as occurs in intensive confinement rearing systems. Under such circumstances, even ostensibly safe threshold limit value (TLV) levels may be far too high. Further, the interactions of a number of different gaseous compounds complicate both the effects of the exposure and the study of it.

Sublethal effects of exposure to manure gas (and by implication to H_2S) have included ocular and nasopharyngeal irritation, opthalmitis, reduced feed and water consumption, growth and productivity, increased blood clotting time and haemorrhaging, increased

respiratory disease, neurologic dysfunction, abortion, and pododermatitis. Experimental proof for the clinical syndromes is in most cases lacking; however, the various clinical reports do have a high degree of consistency.

Recently, the effects of H_2S, NH_3, and combinations of the two gases on ruminants have been studied [219]. This investigation confirmed the serious irritant propery of H_2S including severe and only partially reversible corneal damage and incipient rupture of the eyeball. Epistaxis was a prominent feature at high levels of H_2S, thus providing the first experimental verification of the clinically observed bleeding phenomenon. Feed and water consumption both were reduced about 25% by 150 ppm H_2S; however, effects on respiratory rate and rectal temperature were inconclusive. As well, extensive measurements of haematologic, clinical chemistry, and blood gas parameters including sufhaemoglobin were inconclusive even at 150 ppm exposure for seven days. It was concluded that exposure level rather than duration seemed to be of greatest consequence.

An investigation by Alberta Department of Agriculture listed the symptoms observed during exposure of young pigs to hydrogen sulphide [220]. This was a purely descriptive study and, based on the limited number of animals, concluded that hydrogen sulphide poisoning in domestic animals would occur only under the same conditions responsible for poisoning of humans.

6.2 LABORATORY ANIMALS

Laboratory mice which were maintained under natural environmental conditions near the Waterton gas plant showed no adverse effects as a result of exposure to SO_2. Histological changes were similar in both control and emission zones and were attributed to aging and not to irritant damage because of SO_2 inhalation [213].

Significant reductions in weight gain have been observed in high (10 to 20 ppm) SO_2 concentrations [214]. Reviews of other laboratory animal studies indicated that only concentrations in excess of 1 ppm would produce measureable effects.

Hydrogen sulphide toxicity studies in laboratory animals have been reviewed [210]. In general, effects comparable to those seen in human and domestic animals and wildlife have been observed. A quantitative study of the relative importance of the duration of exposure and concentration of exposure on the lethality of H_2S has been undertaken [221]. The LC_{50} (the concentration of gas which kills 50% of test subjects) was time dependent; higher concentrations of the gas were required to cause death during shorter exposure durations. This result is contrary to the belief that the toxicity of H_2S is determined primarily by concentration and not duration of exposure [220]. The LC_{50} for mice exposed for 10 minutes was 1097 ppm. Although this concentration is outside the normal environmental range, it may occur in an occupational setting or following a catastrophic event such as a gas pipeline fracture.

6.3 CONCLUDING REMARKS

Although normal environmental levels of sulphur gases in Alberta do not seem to pose a serious health hazard to humans or other animals, certain situations exist in which higher levels of sulphur gases may be present. The generation of H_2S and other gases from manure slurry may endanger the health of agricultural workers and their livestock while gas emissions associated with the oil and gas industry have poisoned several hundred industrial workers in Alberta in the last 10 years. Clearly, much has to be learned about the potential adverse health effects of sulphur gases. In particular, data are required concerning the effects of chronic exposure to lower levels of SO_2 and H_2S, alone and in combination with other pollutants. Further, the controversy over the use of nitrite in the treatment of H_2S inhalation must be resolved.

7. MISCELLANEOUS STUDIES

Other published investigations, which are not discussed in the previous sections, are described briefly below.

7.1 EFFECTS ON MATERIALS

Several reports have evaluated and documented the possible atmospheric corrosion in the vicinity of sour gas plants [222-227]. Different types of metal and paint samples were exposed to the environment for different durations. The metal samples included bare mild steel, galvanized steel, Canadian barbed wire, Japanese barbed wire, and telephone wire. Paint samples included red implement paint on metal, red barn paint on cedar, white latex on cedar, and white oil-base paint on cedar. These samples were chosen because of their availability and widespread use.

Atmospheric corrosion rates depend on meteorological conditions, especially humidity, and exposure times. Although observed corrosion rates were quite variable, some general conclusions were possible. At most sampling sites, mild steel showed the highest corrosion rate, followed by Canadian barbed wire, galvanized steel, and Japanese barbed wire. Telephone wire exhibited the lowest corrosion rate. In general, corrosion rates were highest in the vicinity of sour gas plants, followed by urban (Calgary) and agricultural areas. Recent monitoring has suggested that, while corrosion rates for bare mild steel are higher near some gas plants than at urban and agricultural sites, corrosion rates for other metals are lower near gas plants [227]. No studies were available pertaining to the oil sands area.

The condition of the paint samples studies was normal for the exposure time involved, typically one year. All samples showed some degree of fading but were in good condition.

7.2 METHODS OF MONITORING SULPHUR GASES

Various analytical methods, employing physical and chemical principles of measurement, have been developed for monitoring sulphur gases in the environment. A review of the most widely used methods in Alberta has been published recently [228]. Measurement of background air pollutants in clean atmospheres is often a difficult task. Some of the problems experienced in operating commercial instruments in clean atmospheres have been discussed [229].

At present there is no facility in the province which provides a calibration service for instruments operated by private and public agencies. It becomes difficult to compare and evaluate various data sets when procedures of calibration are different. Therefore, there is an urgent need to establish such a facility.

One of the techniques to follow sulphur emissions from a source is that of measuring naturally occurring stable sulphur isotopes as a function of space and time. Its application in environmental studies has already been demonstrated [137, 146, 161, 230-233]. Some of these studies have been reviewed in previous sections. Since the results of the latest study are important, they are presented here to illustrate the usefulness of this technique [233].

Baseline data, including sulphur concentrations, pH of soil and water, and sulphur isotope determinations, were collected to assess the environmental impact of continued operation of the Teepee Creek gas plant in the Peace River region. The following were the significant observations of this study.

1. Neither the pH data nor sulphur isotope compositions of the water or soil samples revealed measureable sulphur loading by the industrial operation;
2. The measured atmospheric SO_2 concentrations were well below air quality standards;

3. Data from the atmospheric sampling array revealed that the directions of highest SO_2 concentrations did not correspond to the direction of the gas processing plant nor did high concentrations relate isotopically to the emission; and
4. In both soil and vegetation samples, increase of sulphur concentration was identified isotopically with mineral layers in the subsurface and not with the industrial operation.

It was concluded that environmental effects could be assessed by future monitoring of isotopic compositions.

8. RESEARCH NEEDS

Although environmental sulphur research in Alberta has increased during the past decade, many gaps still exist in our basic knowledge of the potential effects of sulphur in the environment. Many of these gaps have been identified in earlier sections. Recommendations for future environmental sulphur research, based on the Alberta Sulphur Gas Research Workshop III Proceedings, have been reported previously [116]. Research needs identified in this section are based on the Alberta research literature and on each author's awareness of the current national and international research literature.

8.1 EMISSIONS AND TECHNOLOGY

Projections of future industrial emissions of S compounds in Alberta have been prepared and indicate a considerable increase in annual amounts (Figure 3). Cumulative effects of such emissions will be important over the long term, therefore, it is essential that emissions be minimized to the greatest extent practicable. As control at source is critical, research on recovery technologies should continue. Because of the projected increase in production by oil sands and thermal power plants, research on recovery technology and environmental effects directed at these industries should be intensified.

In the past, no research has been conducted on the effects of gas well blowouts, or other large accidental emissions. A contingency monitoring and research plan needs to be developed for the future study of these situations.

8.2 AIR

Before transport and deposition of sulphur can be interpreted with respect to industrial emissions, the variability of background SO_2 concentration must be understood. Although there have been some investigations of short-range transport, there is considerable uncertainty about the quantitative details of diffusion

in inhomogeneous atmospheres and over complex terrain. Medium- and long-range transport of sulphur gases needs to be investigated. Such studies are essential for the determination of a complete sulphur budget for the province.

The rate of conversion of SO_2 to other compounds is important for the assessment and understanding of the effects of SO_2 emissions and acid precipitation but has not been fully investigated. In addition, research should be conducted on SO_2 oxidation in the aqueous phase, SO_2-ice fog interactions, and plume chemistry of different sources. To date, atmospheric chemistry has not been incorporated into dispersion models for predicting SO_2 concentrations from plumes containing particulates and other contaminants.

It is necessary to increase the knowledge about deposition mechanisms, maximum deposition zones, and to obtain estimates of dry and wet deposition.

8.3 WATER

A definite need exists to further identify and quantify sulphur compounds associated with Alberta's expanding industry. Of particular importance will be the contribution from heavy oils and oil sands extraction plants, for both *in situ* and surface mining and *in situ* coal gasification. Although many sulphur compounds occur naturally, industrially produced compounds must be toxicologically and environmentally investigated.

Because of Alberta's climatic conditions, waste water treatment procedures need to be improved. The efficacy of deep well waste water disposal requires further investigations to prevent the pollution of other potentially usable geological resources.

8.4 SOILS AND VEGETATION

To date, there has not been an integrated research effort by biological and atmospheric scientists. Thus, the relationships between soil chemistry (including acidity) and the amount and form of deposited sulphur have not been clearly defined. There remains

uncertainty about the magnitude of the industrial sulphur gas effect on soil chemistry in the natural environment, because the effect can be masked by natural soil variability. There is also disagreement about using pH alone as an indicator of sulphur gas effects. Further information is required on the rate of change of soil pH and the rate of sulphur uptake, considering such variables as soil cover, texture, and organic content.

The effects of sulphur deposition on micro-organisms present in major litter and mineral forest soil types have not been definitely determined. Long-term studies for determining the rate and composition of sulphur uptake by forest soils under canopies and in stand openings as a function of distance from SO_2 sources should be undertaken. Studies should also be undertaken on the long-term effects of industrial SO_2 on the soil nutrient balance with respect to the maintenance of major forest species. In addition, an increased understanding is needed of the cyclic nature of cation leaching and uptake by forest species.

Effects of sulphur emissions on vegetation in agricultural and natural ecosystems have been studied by many researchers; however, further research is warranted.

The effects on soils and vegetation of mixtures of gases in emissions from power plants, oil sands plants, or urban regions will require study, as there is little information available for Alberta. Further information on physiological response (an indicator of previsual effects), and the permanent or transient nature of visual effects should be obtained.

In order to assess effects of long-term, low-level exposure to sulphur gases or mixtures of gases, research should be conducted within an ecosystem context. Biomonitoring research and determination of assimilative capacities of different ecosystems will assist in the detection of these long-term, low-level impacts. In addition, it will be important to assess the influence of soils or other environmental factors, such as light, temperature, and moisture on

sulphur uptake and plant metabolic responses. Laboratory studies will be necessary to measure relationships between dosage and vegetation responses under a variety of conditions.

8.5 HEALTH

As is the case for soils and vegetation, the full spectrum of sulphur gas effects on health cannot be analyzed until the complete physical and chemical composition of the air (environmental and occupational) is determined. Factors such as the time-dependent concentrations of gas mixtures and particulates, maximum expected dosage (concentration x duration of exposure), and variation with meteorological parameters need to be fully determined. Naturally occurring conditions must be reproduced in a laboratory setting to permit more detailed analyses of potential ill effects.

Health effects have not been observed in normal, average populations, although adverse health effects may not be detectable using present techniques. To date, there have been no studies of abnormal sub-populations composed of physically or pathologically hypersensitive individuals. Long-term studies need to be undertaken as toxic reactions may become evident only after many years of exposure.

There are other areas in which the effects of sulphur gases on health are not completely understood. For example, the time course of toxicity for single and multiple exposures has not been examined in detail (tachyphlaxis, tolerance, or sensitization may be discovered). External influences on toxicity, such as exercise, drugs, and disease, also need to be fully explored. So far, experimental studies have not, in general, been reproducible and the results have not been statistically meaningful. In the next decade, more field experiments that compromise between over-simplified laboratory conditions and complex, multi-variate field conditions will be required.

9. BIBLIOGRAPHY

9.1 CITED REFERENCES

1. United States Department of Agriculture, Forest Service, 1976. Proceedings of First International Symposium on Acid Precipitation and the Forest Ecosystem, Columbus, Ohio, May 12-15, 1975. General Technical Report NE-23, 1976. 1074 pp.

2. American Institute of Chemical Engineering, 1977. Symposium on atmospheric sulphur compounds. 7th Annual Meeting, New York, New York, November 13-17, 1977.

3. Husar, R.B., J.P. Lodge, Jr. and D.J. Moore (Eds.), 1977. Sulfur in the atmosphere. Proceedings of International Symposium, Dubrovnik, Yugoslavia, September 7-14, 1977. Atmospheric Environment. 12(1-3):1-796.

4. National Research Council of Canada, NRC Associate Committee on Scientific Criteria for Environmental Quality, 1977. Sulphur and its inorganic derivatives in the Canadian environment. Publication No. NRCC 15015. Ottawa. 426 pp.

5. National Research Council, Committee on Medical and Biological Effects of Environmental Pollutants, Subcommittee on Hydrogen Sulfide, 1979. Hydrogen sulfide. University Park Press, Baltimore, Maryland. 183 pp.

6. Nriagu, J.O. (Ed.), 1978. Sulphur in the environment. Part I: The atmospheric cycle. John Wiley and Sons, Inc., New York, New York. 464 pp.

7. Nriagu, J.O. (Ed.), 1978. Sulphur in the environment. Part II: Ecological impacts. John Wiley and Sons, Inc., New York, New York. 482 pp.

8. National Academy of Sciences, 1978. Sulphur oxides. Washington, D.C. 209 pp.

9. Natusch, D.F.S. and B.J. Slatt, 1978. Hydrogen sulphide as an air pollutant. Air Pollution Control, Volume 3, Chapter 9, pp. 459-518.

10. Sugden, T.M. (Ed.), 1979. Pathways of pollutants in the atmosphere. The Royal Society, London. 169 pp.

11. Canada Department of the Environment, 1978. A nationwide inventory of emissions of air contaminants (1974). Air Pollution Control Directorate. Report EPS 3-AP-78-2. 145 pp.

12. Sandhu, H.S., 1979. Industrial sulphur emissions for Alberta 1974-1978. Alberta Department of the Environment, Research Secretariat, Edmonton. 21 pp.

13. Government of the Province of Alberta, 1971. The Energy Resource Conservation Act. Statutes of Alberta. Chapter 30.

14. Alberta Energy Resources Conservation Board, 1972. Status of environmental protection in the Alberta energy resource industries. Calgary.

15. Alberta Energy Resources Conservation Board, 1974. Acid gas content of Alberta natural gas to April 30, 1974. Calgary. Report 74-23. 96 pp.

16. Alberta Energy Resources Conservation Board, 1974. Review of the Alberta coal industry - 1973. Calgary.

17. Alberta Energy Resources Conservation Board, 1975. Reserves of crude oil, gas, natural gas liquids, and sulphur - province of Alberta. Calgary. Various paging.

18. Environment Conservation Authority, 1972. Environmental effects of the operation of sulphur extraction gas plants. Proceedings of public hearings. Parts I, II, and III. Edmonton. 1743 pp.

19. Environmentl Conservation Authority, 1972. Environmental effects of the operation of sulphur extraction gas plants. Report and recommendations. Edmonton. 128 pp.

20. Environment Conservation Authority, 1973. Environmental effects of the operation of sulphur extraction gas plants. Summary of the public hearings. Edmonton. 159 pp.

21. Government of the Province of Alberta, 1971. The Department of the Environment Act. Statutes of Alberta. Chapter 24.

22. Government of the Province of Alberta, 1971. The Clean Air Act. Statutes of Alberta. Chapter 16.

23. Government of the Province of Alberta, 1971. The Clean Water Act. Statutes of Alberta. Chapter 17.

24. Government of the Province of Alberta, 1973. The Land Surface Conservation and Reclamation Act. Statutes of Alberta. Chapter 34.

25. Alberta Department of the Environment, 1972. Gas processing plant standards: air pollution control and emission standards from new and existing plants. Standards and Approvals Division, Edmonton. 5 pp.

26. Alberta Department of the Environment, 1976. Air monitoring directive - sour gas industry. Pollution Control Division, Edmonton. Report AMD-76-1. 34 pp.

27. Alberta Department of the Environment, 1976. Source sampling code. Standards and Approvals Division, Edmonton. Publication SSC-1/76. 130 pp.

28. Alberta Department of the Environment, 1978. Guidelines for plume dispersion calculations. Standards and Approvals Division, Edmonton. 108 pp.

29. Alberta Department of Health, 1976. Air pollution control at gas processing and sulphur recovery plants. Environmental Health Services Division, Edmonton. 90 pp.

30. Alberta Oil Sands Environmental Research Program, 1977. Alberta Oil Sands Environmental Research Program Policy and Direction. Alberta Oil Sands Environmental Research Program, Edmonton. 25 pp.

31. Smith, S.B. (Ed.), 1979. Alberta Oil Sands Environmental Research Program interim report covering the period April 1975 to November 1978. Alberta Oil Sands Environmental Research Program, Edmonton. 101 pp.

32. Hocking, D. and D. Reiter (Eds.), 1973. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 1, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. Report NOR-X-72. 196 pp.

33. MacDonald, W.R. and H.S. Sandhu (Eds.), 1975. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. 174 pp.

34. Sandhu, H.S. and M. Nyborg (Eds.), 1977. Proceedings and Technical Summary of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. 334 pp.

35. Clarke, K.A. and S.M. Blair, 1927. The bituminous sands of Alberta: occurrence and separation of bitumen from sand. Alberta Research Council. Report Number 18. Various paging.

36. Webber, H.J. and G.A. Warne, 1979. Sulphur emissions, Alberta energy industries. Presented at PNWIS-APCA Annual Meeting, Edmonton, Alberta, November 7-9, 1979. 20 pp.

37. Klemm, R.F., 1972. Environmental effects of the operation of sulphur extraction gas plants. Environment Conservation Authority, Edmonton. 116 pp.

38. George, Z.M., 1976. Advances in Claus reaction and related reactions. Phosphorus and Sulphur. 1:315-322.

39. Kerr, R.K., 1976. The Claus process: capability/thermodynamics. Energy processing/Canada. 68(6):28-35.

40. Kerr, R.K., 1976. The Claus process: thermodynamics of sulphane production. Energy Processing/Canada. 69(6):48-51.

41. Kerr, R.K., 1976. The Claus process: reaction furnace/burner operation. Energy Processing/Canada. 69(5):42-46.

42. Kerr, R.K., H.G. Paskall and N. Ballash, 1976. The Claus process: catalytic kinetics/Part I - the modified Claus reaction. Energy Processing/Canada. 69(1):66-72.

43. Kerr, R.K. and H.G. Paskall, 1976. The Claus process: catalytic kinetics/Part II - COS and CS_2 hydrolysis. Energy Processing/Canada. 69(2):38-44.

44. Kerr, R.K., H.G. Paskall, N. Ballash and W. Quiring, 1976. The Claus process: catalytic kinetics/Part III - deactivation mechanisms and catalyst evaluations. Energy/Processing Canada. 69(3):40-51.

45. Kerr, R.K., H.G. Paskall and L.C. Biswanger, 1976. Sulphur plant waste gases - incineration kinetics and fuel consumption. Energy Processing/Canada. 68(4):32-40.

46. Kerr, R.K. and R.P. Rankine, 1974. High efficiency Claus plants. Proceedings of 53rd Gas Processors' Association convention, Denver, Colorado, March 25-27, 1974.

47. Dalla Lana, I.G., B.K. Cho and C.L. Liu, 1974. A graphical approach for modified Claus processing calculations, Part I: once through processes. Proceedings of Canadian Natural Gas Processors' Association, research seminar, Calgary, Alberta, November 29, 1974. 18 pp.

48. Dalla Lana, I.G., 1978. Catalysis research on the modified Claus process. Energy Processing/Canada. 70(4):34-38.

49. Dalla Lana, I.G., C.L. Liu and B.K. Cho, 1976. The development of a kinetic model for rational design of catalytic reactors in the modified Claus process. Proceedings of 4th International Symposium on Chemical Reaction Engineering, Heidelburg, Germany, April 5-9, 1976. 10 pp.

50. Rankine, R.P., R.K. Kerr and H.G. Paskall, 1973. Potential efficiency of the conventional Claus sulphur recovery process. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 2, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. Report NOR-X-72.

51. Paskall, H.G., 1977. Sulphur plant waste gas incineration - how to optimize to save energy. Energy Processing/Canada. 69(4):36-44.

52. Morin, M.M. and Y.M. Philardeau, 1976. Sulphreen process experienced at Ram River (Alta.). Presented at Canadian National Gas Processing Association meeting, Calgary, Alberta, June 9, 1976. 24 pp.

53. Morin, M.M. and Y.M. Philardeau, 1977. Sulphreen process experience at Ram River. Energy Processing/Canada. 69(5):30-37.

54. Naber, J.E., 1973. Reduce sulphur emission with SCOT process. Energy Processing/Canada. 61(1):32-28.

55. Hyne, J.B., 1972. Methods for desulphurization of effluent gas streams. The Oil and Gas Journal. 70(35):64-78.

56. Barry and Richardson Consulting Engineers, 1972. Sulphur plant stack gas processing study for the East Calgary plant. Petrogas Processing Limited, Calgary. 37 pp.

57. Goar, B.G., 1975. Claus tail gas clean-up processes, Part I. Energy Processing/Canada. 67(3):26-34.

58. Goar, B.G., 1976. Claus tail gas clean-up processes, Part II. Energy Processing/Canada. 68(3):32-35.

59. Dingle, H.B., 1972. Conversion of sulfur dioxide to elemental sulfur in stack gas. University of Calgary, Department of Chemical Engineering, Calgary. M.Sc. Thesis.

60. Mohtadi, M.F. and H.B. Dingle, 1973. Removal of sulphur dioxide from wet stack gases of sour gas plants. Paper presented at Canadian National Gas Processing Association meeting, Calgary, Alberta, November 30, 1973.

61. Western Research and Development Limited, 1976. Evolution of pollution abatement as applied to the Alberta oil sands. Alberta Department of the Environment, Edmonton. 162 pp.

62. Suntech Incorporated (Central Engineering), 1976. Feasibility study of power plant particulate and SO_2 emissions control. Great Canadian Oil Sands Limited. 59 pp.

63. Goforth, R.R., 1977. Application of best practicable technology in air pollution control for the Syncrude project. Proceedings of Second Pacific Chemical Engineering Congress (PACHEC 1977), Denver, Colorado. Library Congress #77-92-322. Inter American Confederation of Chemical Engineering. pp. 1287-1294.

64. Djurfors, S., 1977. Possible technologies for air pollution control at the Syncrude plant. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton, pp. 85-93.

65. New Norway Scientific Committee, 1974. Regarding a gas well blowout October 2, 1973 near Camrose. Alberta Department of the Environment, Edmonton. 42 pp.

66. Alberta Energy Resources Conservation Board, 1978. In the matter of an uncontrolled flow from the well Amoco Pacific Brazr. Inquiry Report 78-8. 16 pp.

67. Angle, R.P., 1979. Atmospheric diffusion characteristics for Alberta. Pollution Control Division, Alberta Department of the Environment, Edmonton (in preparation).

68. Grandia, K.L., 1975. The use of twin-engine aircraft for the determination of the structure and concentration of effluent plumes. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 42-49.

69. Lee, G.K., H. Whaley and J.G. Gainer, 1973. Plume dispersion research at natural-gas sulphur-extraction plants. Department of Energy, Mines and Resources, Mines Branch, Ottawa. Report R265. 35 pp.

70. Havlena, J.J., D. Hocking and R.D. Rowe, 1975. The photography of sulphur recovery plant plumes. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of Environment, Research Secretariat, Edmonton. pp. 30-31.

71. Rowe, R.D., 1973. Short and medium range atmospheric diffusion in the Alberta environment. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 1, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. pp. 26-30.

72. Leahey, D.M. and R.D. Rowe, 1975. Observational studies of atmospheric diffusion processes over irregular terrain. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 64-65.

73. Benjamin, S.F., J.J. Havlena and R.D. Rowe, 1977. Air pollution studies on a ridge near a sour gas plant. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 39-51.

74. Benjamin, S.F., J.J. Havlena and R.D. Rowe, 1978. Field investigations of the dispersion of pollution across a ridge. Proceedings of 9th International Technical Meeting on Air Pollution Modelling and Its Application, Toronto, Ontario, August, 1978. pp. 46-55.

75. Chung, K.P., 1979. Tetroon flights across a two-dimensional ridge under stable atmospheric conditions. University of Calgary. M.Sc. Thesis.

76. Lee, C.Z., 1979. Plume trajectories across a ridge under stable atmospheric conditions. University of Calgary. M.Sc. Thesis.

77. Wilson, D.J., 1977. Plume diffusion over downwind two-dimensional hills: a wind tunnel study. Research Project 75-8, Alberta Department of the Environment, Edmonton.

78. Leahey, D.M., 1973. A study of air flow over irregular terrain. Atmospheric Environment. 8:783-791.

79. Whaley, H., G.K. Lee and J.G. Gainer, 1977. High volume flaring of sour gas under limited mixing conditions. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 94-108.

80. Beauchemin, P.A., W. Nader and G. Earl, 1971. Ground level concentrations of SO_2 around sulphur recovery plants in Alberta versus predicted. Proceedings of Air Pollution Control Association Annual Meeting, Calgary, Alberta, November 21-23, 1971. 18 pp.

81. Leung, T., M.F. Mohtadi and R.D. Rowe, 1972. Evaluation of stack gas sizing formula. Gas Processing/Canada. 64(5):40-42.

82. Mohtadi, M.F. and R.D. Rowe, 1973. Dispersion of plumes from sulphur recovery plants. Gas Processing/Canada. 65(5):16-20.

83. Fortems, C.C., 1975. Computer simulation of effluent SO_2 plumes in the Whitecourt area. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 32-41.

84. Intercomp Resource Development and Engineering Limited, 1972. An air quality study, Petrogas plant, Balzac, Alberta. Petrogas Processing Ltd. 48 pp.

85. Aziz, K., J.K. Donnelly, and J.P.A. Wallis, 1973. Computer simulation of pollutant dispersion: single stack and air shed models. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 1, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. pp. 32-43.

86. Wallis, J.P.A., K. Aziz, and J.K. Donnelly, 1975. A report on computer modelling of plume dispersion. University of Calgary, Department of Chemical Engineering, Calgary.

87. Strosher, M.M., 1978. Ambient air quality in the AOSERP study area, 1977. Alberta Oil Sands Environment Research Program, Edmonton. AOSERP Report 30. 74 pp.

88. Schwabe, P. and A. Kumar, 1979. Thermal boundary layer calculations for the tar sands area. Environmental Affairs, Syncrude Canada Ltd., Edmonton. 24 pp.

89. Kumar, A., 1978. Numerical modelling of the development of the thermal boundary layer near a synthetic crude oil plant. Professional Paper 1978-4, Syncrude Canada Ltd., Edmonton. 32 pp.

90. Barrie, L.A. and J.L. Walmsley, 1978. A study of sulphur dioxide deposition velocities to snow in northern Canada. Atmospheric Environment. 12:2321-2332.

91. Whaley, H., G.K. Lee, M.S. Hirt and A.D. Galbraith, 1972. Joint study of plume dispersion from the Great Canadian Oil Sands complex, Tar Island, Alberta, 1971. Department of Energy, Mines and Resources, Mines Branch, Fuels Research Centre, Ottawa. Divisional report DR FRC 72/79 - CCRL. 60 pp.

92. Whaley, H. and G.K. Lee, 1974. Ground level plume impingement patterns derived from aerial dispersion measurements at the Great Canadian Oil Sands complex, 1971. Department of Energy, Mines and Resources, Mines Branch, Fuels Research Centre, Ottawa. Divisional Report FRC 74/30 - CCRL. 8 pp.

93. Fanaki, F., 1978. Meteorology and air quality winter field study in the AOSERP study area, March 1976. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Atmospheric Environment Service. AOSERP Report 27. 249 pp.

94. Fanaki, F., R. Mickle, M. Lusis, J. Kovalick, J. Markes, F. Froude, J. Arnold, A. Gallant, S. Melnichuk, D. Brymer, A. Gaudenzi, A. Moser, and D. Bagg, 1979. Air System field study in the AOSERP study area. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Atmospheric Environment Service. AOSERP Report 24. 182 pp.

95. Davison, D.S., C.J. Fortems and K.L. Grandia, 1977. Plume dispersion measurements from an oil sands extraction plant, March 1976. Prep. for the Alberta Oil Sands Environmental Research Program by INTERA Environmental Consultants Ltd. AOSERP Report 13. 195 pp.

96. Davison, D.S. and E.D. Leavitt, 1979. Analysis of AOSERP plume sigma data. Prep. for the Alberta Oil Sands Environmental Research Program by INTERA Environmental Consultants Ltd. AOSERP Report 63. 251 pp.

97. Kumar, A. and S. Djurfors, 1977. General expressions for maximum and critical ground level concentrations. Professional Paper 1977-6, Syncrude Canada Ltd., Edmonton. 17 pp.

98. Djurfors, S., 1977. On the rise of vertical plumes. Professional Paper 1977-8, Syncrude Canada Ltd., Edmonton. 12 pp.

99. Murray, W. and J. Kurtz, 1976. A predictive study of the dispersion of emissions from the Syncrude Mildred Lake plant. Environmental Research Monograph 1976-1, Syncrude Canada Ltd., Edmonton. 128 pp.

100. Walmsley, J.L., and D.L. Bagg, 1977. Calculations of annual averaged sulphur dioxide concentrations at ground level in the AOSERP study area. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Atmospheric Environment Service. AOSERP Report 19. 40 pp.

101. Kumar, A., 1979. The effects of cross-wind shear on horizontal dispersion. Proceedings of 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979. 16 pp. See also: Kumar, A., 1978. Pollutant dispersion in the planetary boundary layer. Syncrude Canada Ltd., Professional Paper 1978-1. 182 pp.

102. Kumar, A., 1979. Estimation of atmospheric dispersion coefficients for elevated releases. Preprint of Fourth Symposium on Turbulence, Diffusion and Air Pollution, Reno, Nevada, January 15-18, 1979. American Meteorological Society, Boston. pp. 19-26.

103. Kumar, V., 1973. Sulfur recovery plant plume rise. University of Calgary, Department of Mechanical Engineering. M. Sc. Thesis. 104 pp.

104. Alberta Petroleum Industry - Government Environmental Committee, 1978. H_2S isopleth prediction, phase I: model sensitivity study. 49 pp.

105. Wilson, D.J., 1979. The release and dispersion of gas from pipeline ruptures. Alberta Department of the Environment, Edmonton. 91 pp.

106. Alberta Petroleum Industry - Government Environmental Committee, 1979. H_2S isopleth prediction, phase II: pipe burst study 115 pp.

107. Sandhu, H.S., 1973. The atmospheric photochemistry of SO_2. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 1, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. pp. 53-56.

108. Mohtadi, M.F. and E.Y. Gyuse, 1975. Chemical transformation pathways of SO_2 gas in the atmosphere. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 20-29.

109. Rowe, R.D., 1976. A sulphur budget for sour gas plants. Water, Air, and Soil Pollution. 6:321-327.

110. Bottenheim, J.W. and O.P. Strausz, 1977. Review of pollutant transformation processes relevant to the Alberta oil sands area. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Alberta, Hydrocarbon Research Centre. AOSERP Report 25. 166 pp.

111. Calvert, J.G., F. Su, J.W. Bottenheim and O.P. Strausz, 1978. Mechanisms of the homogeneous oxidation of sulphur dioxide in the troposhere. Atmospheric Environment. 12:197-226.

112. Boyle, J.M., 1975. Atmospheric reactions of sulfur dioxide and monoterpenes. University of Calgary (Committee on Resources and Environment), Calgary. M.Sc. Thesis. See also: Boyle, J.M., 1976. The environmental sulfur cycle. University of Calgary, Environmental Sciences Centre, Kananaskis. 45 pp.

113. Rowe, R.D., M.F. Mohtadi, J.J. Havlena, D.I. Exall, J.M. Boyle and S.F. Benjamin, 1977. The short range chemistry of sour gas plant plumes. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 27-38.

114. Lusis, M.A., K.G. Anlauf, L.A. Barrie and H.A. Wiebe, 1977. Plume chemistry studies at a northern Alberta power plant. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 68-84.

115. Bottenheim, J.W., O.P. Strausz and J.G. Calvert, 1977. Evaluation of the major homogeneous oxidation steps of SO_2 in the Alberta troposhere, and computer simulation of the homogeneous oxidation of SO_2 in an urban polluted air parcel. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 52-67.

116. Nyborg, M., R.L. Halstead, A.A. Loman and H.S. Sandhu, 1978. Background and recommendations for environmental sulphur research in Alberta. Alberta Department of the Environment, Research Secretariat, Edmonton. 7 pp.

117. Walker, D.R., 1969. Sulphur in precipitation in central Alberta. Canadian Journal of Soil Science. 49:409-410.

118. Summers, P.W., 1970. Scavenging of SO_2 by convective storms. Proceedings of In Precipitation Scavenging, Richland, Washington, June 2-4, 1970. Environmental Council, Washington, D.C., U.S.A. pp. 305-316.

119. Summers, P.W. and B. Hitchon, 1972. Source and budget of sulphate in precipitation from central Alberta, Canada. Journal of Air Pollution Control Association. 32(3):194-199.

120. Klemm, R.F., 1977. Sulfur in Alberta precipitation - consequences of three years of survey. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 305-317. See also: Klemm, R.F., 1977. Sulfur in precipitation, contribution to an Alberta sulfur inventory. Alberta Department of the Environment, Edmonton. 126 pp.

121. Caiazza, R., K.D. Hage and D. Gallup, 1978. Wet and dry deposition of nutrients in central Alberta. Water, Air, and Soil Pollution. 9:309-314.

122. Barrie, L.A. and D.M. Whelpdale, 1977. Wintertime sulphur deposition measurements in the Athabasca oil sands area. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 318-333.

123. Benjamin, S.F., 1975. The fate of SO_2 from sour gas plants. University of Calgary, Department of Chemical Engineering, Calgary. 33 pp.

124. Western Research and Development Limited, 1978. Derivation of first order estimates of sulphur deposition in the region of representative point sources. Alberta Department of the Environment, Edmonton. Various paging.

125. Taylor, G., 1979. The potential for acid precipitation related environmental problems due to the development of the Alberta oil sands near Fort McMurray, Alberta. Faculty of Environmental Design, University of Calgary. 57 pp.

126. Alberta Department of the Environment, 1978. Precipitation quality monitoring program in Alberta. Air Quality Control Branch, Pollution Control Division, Edmonton.

127. Canada Department of the Environment, 1978. Canadian precipitation sampling network. Atmospheric Environment Service, Toronto.

128. Milne, K.C., 1974. The treatment of waste waters from sour gas processing plants, Part I. Energy Processing/Canada. 67(2):24-28.

129. Milne, K.C., 1975. The treatment of waste waters from sour gas processing plants, Part II. Energy Processing/Canada. 67(3):30-34.

130. Duffy, J.J. and A. Smandych, 1977. Some effects of sulphur storage on water quality. Proceedings of Alberta Sulphur Gas Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 294-304.

131. Kessick, M.A. and A.M. Jobson, 1978. Clay tailings from Alberta oil sands and other sources - a review. Alberta Department of the Environment, Edmonton. Report 1978/2. 87 pp.

132. Jantzie, T.D., 1977. A synopsis of information relating to aquatic ecosystems toxicology within the Alberta Oil Sands area. Prep. for the Alberta Oil Sands Environmental Research Program by Renewable Resources Consulting Services Ltd. AOSERP Project AF 3.1.2. 70 pp.

133. Strosher, M.T. and E. Peake, 1976. The evaluation of waste-waters from an oil sands extraction plant. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Calgary, Environmental Sciences Centre (Kananaskis). AOSERP Report 5. 103 pp.

134. Strosher, M.T. and E. Peake, 1978. Characterization of organic constituents in waters and wastewaters of the Athabasca Oil Sands mining area. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Calgary, Environmental Sciences Centre (Kananaskis). AOSERP Report 20. 70 pp.

135. Hsu, H. and G.W. Hodgson, 1977. Organic compounds of sulfur: initial data for soils and streams in Alberta. Proceedings of Alberta Sulphur Gas Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 246-263.

136. Costerton, W.T., 1979. Department of Biology, University of Calgary (private communication).

137. Hitchon, B. and H.R. Krouse, 1979. Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada-III. Stable isotopes of oxygen, carbon and sulphur. Geochimica et Cosmochimica Acta. 36:1337-1357.

138. Miller, R.B. and H.B. Watkins, 1946. An experiment in the control of the cestode, *Triaenophorus crassus* Forel. Canadian Journal of Research. 24(6):175-179.

139. Hesslein, R.H., 1979. Lake acidification potential in the Alberta Oil Sands Environmental Research Program Study Area. Prep. for the Alberta Oil Sands Environmental Research Program, Edmonton by the Freshwater Institute, Environment Canada. AOSERP Report 71. 36 pp.

140. Holowaychuk, N., 1979. Soil properties that affect the retention of airborne sulphur in Alberta soils. Alberta Research Council, Soils Division, Edmonton. 33 pp.

141. Nyborg, M., J. Crepin, D. Hocking and J. Baker, 1977. Effect of sulphur content and acidity of soils in Alberta, Canada. Water, Air, and Soil Pollution. 7:439-448.

142. Dick, A.C. and D. Walker, 1975. Adsorption of atmospheric sulphur gases by bare soils. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 77-83.

143. Legge, A.H., D.R. Jacques, G.W. Harvey, H.R. Krouse, H.M. Brown, E.C. Rhodes, M. Nosal, H.U. Schellhase, J. Mayo, A.P. Hartgerink, P.F. Lester, R.G. Amundson and R.B. Walker, 1978. Sulphur gas emissions in the boreal forest: the West Whitecourt case study II, final report. The Whitecourt Environmental Study Group, University of Calgary, Environmental Sciences Center, Kananaskis.

144. Nyborg, M., A.C. Dick, J.M. Crepin, R.F. Klemm, J. Baker and D. Hocking, 1975. Current results on fate of atmospheric SO_2 and its effect on soil, water and vegetation. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 66-76.

145. Nyborg, M. and McKinnon, Allen and Associates Limited, 1973. Atmospheric sulphur dioxide: effects on the pH and sulphur content of rain and snow; addition of sulphur to surface waters, soil and crops; and acidification of soils. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 1, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. pp. 79-97.

146. Krouse, H.R., 1973. Sulphur isotope abundances and environmental assessment. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 1, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. pp. 57-78.

147. Loman, A.A., 1975. Alberta ambient air quality standards for sulphur dioxide, foliar sulphur dioxide symptoms on forest vegetation and impact on growth and vigor. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton, pp. 139-140.

148. Loman, A.A., R.A. Blauel and D. Hocking, 1972. Sulphur dioxide and forest vegetation. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. Report NOR-X-49. 20 pp.

149. Nyborg, M. and D.R. Walker, 1977. An overview - the effects of sulphur dioxide emission on the acidity and sulphur content of soils. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 165-195.

150. Shipley, B.L., 1975. Short and long term effects of sulphur gas emissions on gray wooded and dark gray wooded soils as evidenced by studies in the Whitecourt and Edson forest regions of Alberta. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 84-93.

151. Baker, J., D. Hocking and M. Nyborg, 1977. Acidity of open and intercepted precipitation in forests and effects on forest soils in Alberta, Canada. Water, Air, and Soil Pollution. 7:449-460.

152. Hocking, D., and M. Nyborg, 1974. The problem of soil acidification by sulphur dioxide. Proceedings of Workshop on Reclamation of Disturbed Lands in Alberta, Edmonton, Alberta, March 27-28, 1974. Canada Department of the Environment, Northern Forest Research Centre, Edmonton.

153. Lowe, L.E., 1965. Sulphur fractions of selected Alberta soil profiles of the chernozemic and podzolic orders. Canadian Journal of Soil Science. 45(3):297-303.

154. Nyborg, M., 1969. Sulphur deficiencies in some soils of the Peace River region. Proceedings of Alberta Soils Advisory Committee meeting, Edmonton. Alberta Department of Agriculture, Plant Industry Division, Edmonton.

155. Walker, D.R., 1971. Emission of sulfur oxides into the atmosphere and the sulfur content of Alberta soils. Proceedings of 1971 Annual Air Pollution Control Association meeting, Calgary, Alberta, November 21-23, 1971. 10 pp.

156. Nyborg, M. and C.F. Bentley, 1971. Sulphur deficiencies in rapeseed in cereal grain. University of Alberta, Edmonton. Agriculture Bulletin. Summer, Number 15. 13 pp.

157. Alberta Institute of Agrologists, 1972. The role of sulphur as a nutrient in agricultural production in Alberta. Environment Conservation Authority, Edmonton. 14 pp.

158. Carson, J.A., 1972. A projection of potential sulfur deficient soils in Alberta. Alberta Department of Agriculture, Soil and Feed Testing Laboratory, Edmonton. 9 pp.

159. Penney, D.C., M. Nyborg, P.B. Hoyt, W.A. Rice, B. Siemens and D.H. Laverty, 1977. An assessment of the soil acidity problem in Alberta and northeastern British Columbia. Canadian Journal of Soil Science. 57:157-164.

160. Walker, D.R., 1971. Selenium in forage species in central Alberta. Canadian Journal of Soil Science. 51:506-508.

161. Krouse, H.R., H.M. Brown, W.E. Winner and J.D. Bewley, 1977. A stable sulphur isotope labelling technique for assessing sulphur uptake. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 264-278.

162. Lore, J.A., E.A. McCulloch, S.D. Allen and A.W. James, 1977. The effect of SO_2 emissions on potted soils around the Shell Waterton gas plant. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 196-202.

163. Lore, J.A., E.A. McCulloch, S.D. Allen and A.W. James, 1977. The effect of SO_2 emissions on natural soil profiles around the Shell Waterton gas plant. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 203-212.

164. Hsu, H. and G.W. Hodgson, 1977. Selenium in Alberta agriculture. Unpublished Project Report, Kananaskis Environmental Sciences Centre, University of Calgary, Kananaskis. 12 pp.

165. Laverty, D.H. and J.A. Carson, 1977. Comparison of soil pH in farm fields located at various distances from SO_2 sources. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 237-245.

166. Intera Environmental Consultants Limited, 1976. Report on environmental impact surveys of the Pine Creek gas field 1975. Hudson Bay Oil and Gas Ltd., Calgary. 161 pp.

167. Loman, A.A., 1976. Sulphur dioxide impact at West Whitecourt. Energy Processing/Canada. 68(3):22-28.

168. Environment Resources Airborne Sciences Limited, 1973. A study of the effects of sulphur compounds on the environment of the Whitecourt district of Alberta. Whitecourt Environmental Study Group, University of Calgary, Environment Science Center, Kananaskis. 433 pp.

169. Hocking, D., 1975. Effects on the forest of sulphur dioxide from a sulphur fire near Edson, Alberta. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. Report NOR-X-139. 8 pp.

170. Loman, A.A. 1975. An impact assessment of forest vegetation and soils within a seven mile radius of the Great Canadian Oil Sands complex. Great Canadian Oil Sands Ltd. 83 pp.

171. Webster, G.R. and D.A. McCoy, 1974. Effects of fertilizers on soil acidity. University of Alberta, Department of Agriculture, Edmonton, Alberta. Agriculture Bulletin. 1974, Fall. 25:6-7.

172. Baker, J., 1977. Observations on nutrients levels in rainfall, lodgepole pine foliage, and soils surrounding two sulfur gas extraction plants at Strachan, Alberta. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 138-159.

173. Nyborg, M., 1974. Reclamation of soils and water made acid by windblown sulphur dust. Proceedings of Workshop on Reclamation of Disturbed Lands in Alberta, Edmonton, Alberta, March 27-28, 1974. Canada Department of the Environment, Northern Forest Research Center, Edmonton. pp. 55-70.

174. Bertrand, R.A., 1973. Reclaiming of soils made barren by sulphur from gas processing plants. University of Alberta, Department of Soil Science. M.Sc. Thesis.

175. Malhotra, S.S., 1976. Effects of sulphur dioxide on biochemical activity and ultrastructural organization of pine needle choroplasts. New Phytol. 76:239-245.

176. Malhotra, S.S., 1977. Effects of aqueous sulphur dioxide on chlorophyl destruction in *Pinus contorta*. New Phytol. 78:101-109.

177. Malhotra, S.S. and D. Hocking, 1976. Biochemical and cytological effects of sulphur dioxide on plant metabolism. New Phytol. 76:227-237.

178. Dick, A.C., 1974. Effects of fertilizers on nitrogen-sulphur relationships. University of Alberta, Department of Soil Science, Edmonton. M.Sc. Thesis. 53 pp.

179. Penney, C. and J.A. Carson, 1977. Status of soil acidity and sulfur deficiency in Alberta. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 219-236.

180. Walker, D.R., and G. Doornenbal, 1972. Soil sulphate II. An index of the sulphur available to legumes. Canadian Journal of Soil Science. 52:261-266.

181. Penney, D.C., 1973. Crop responses to liming on acid soils of Alberta and northeastern British Columbia. University of Alberta, Department of Soil Science. M.Sc. Thesis.

182. Massey, D.L., 1973. The effect of sulphur on selenium uptake by plants and selenium deficiency in animals. Alberta Department of Agriculture, Soils Branch, Edmonton. 17 pp.

183. Sibbald Group, 1972. A report on crop and soil conditions in a 30 square mile area surrounding the Petrogas Processing Limited plant at Balzac, Alberta. Petrogas Processing Limited, Calgary. 37 pp.

184. Loman, A.A., 1973. Sulphur dioxide and forest vegetation. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 1, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. pp. 106-110.

185. Hocking, D., 1975. Interim report on long-term impact on the forest of emissions from a sulphur extraction plant. Proceedings of Alberta Sulphur Gas Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 132-138.

186. Winner, W.E., J.D. Bewley and H.R. Krouse, 1977. Variations in coverage, diversity, and sulfur isotopes in mosses along two SO_2-stress gradients in white spruce stands near Fox Creek, Alberta. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 122-137.

187. Legge, A.H. and R.L. Findlay, 1977. Impact of sulphur gas plant emission on the forest ecosystem: the Whitecourt environmental study. Presented at 27th Canadian Chemical Engineering Conference and Alberta Sulphur Research Symposia, Calgary, Alberta, October 23-27, 1977.

188. Intera Environmental Consultants Limited, 1974. Whitecourt environmental study, 1973. Whitecourt Environmental Study Group. University of Calgary, Environmental Science Centre, Kananaskis.

189. Harvey, G.W. and A.H. Legge, 1979. The effect of sulphur dioxide upon the metabolic level of adenosine triphosphate. Canadian Journal of Botany. 57(7):759-764.

190. Malhotra, S.S., 1979. Interim report on physiology and mechanisms of air-borne pollutant injury to vegetation, 1975 to 1978. Prep. for the Alberta Oil Sands Environmental Research Program by Canadian Forestry Service, Northern Forest Research Centre. AOSERP Report 45. 38 pp.

191. Malhotra, S.S., and P.A. Addison, 1979. Interim report on symptomology and threshold levels of air pollutant injury to vegetation, 1975 to 1978. Prep. for the Alberta Oil Sands Environmental Research Program by Canadian Forestry Service, Northern Forest Research Centre. AOSERP Report 44. 13 pp.

192. Addison, P.A. and S.S. Malhotra, 1979. Interim report on symptomology and threshold levels of air pollutant injury to vegetation, 1978-79. Prep. for the Alberta Oil Sands Environmental Research Program by the Northern Forest Research Centre. AOSERP O.F. 1. 17 pp.

193. Khan, A.A. and S.S. Malhotra, 1977. Effects of aqueous sulphur dioxide on pine needle glycolipids. Photochemistry. 16:539-543.

194. Malhotra, S.S., P.A. Addison and A.A. Khan, 1979. Semi-annual (April-September, 1979) progress report on AOSERP Project LS-3. Northern Forest Research Center, Canadian Forestry Service, Edmonton. (unpublished) 6 pp.

195. Malhotra, S.S. and A.A. Khan, 1979. Interim report on physiology and mechanisms of airborne pollutant injury to vegetation, 1978-79. Prep. for the Alberta Oil Sands Environmental Research Program by the Northern Forest Research Centre. AOSERP O.F. 2. 23 pp.

196. Core Laboratories - Canada Limited, 1978. Annual forest monitoring survey for Aquitaine Company of Canada Ltd. File 7044-9162. 28 pp.

197. Lee, T.K. and D.H. Vitt, 1973. A preliminary study of the effects of air pollution on lichen and bryophyte vegetation near Edmonton, Alberta. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta November 1, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. pp. 129-140.

198. Skorepa, A.C. and D.H. Vitt, 1975. A quantitative analysis of lichen vegetation in relation to SO_2 pollution at Rocky Mountain House, Alberta. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 142.

199. Lulman, P.D., W. Petersen and G.W. Douglas, 1977. A lichen network as an early warning monitor of industry air emissions. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 154-164.

200. Case, J.W., 1976. Lichens as bio-indicators of air pollution in west-central Alberta: a progress report. Alberta Environmental Research Trust, Edmonton. 98 pp.

201. Addison, P.A. and J. Baker, 1979. Interim report on ecological benchmarking and biomonitoring for detection of airborne pollutant effects on vegetation and soils, 1978-79. Prep. for the Alberta Oil Sands Environmental Research Program by the Northern Forest Research Centre. AOSERP O.F. 3. 17 pp.

202. Addison, P.A., and J. Baker, 1979. Interim report on ecological benchmarking and biomonitoring for detection of air-borne pollutant effects on vegetation and soils, 1975 to 1978. Prep. for the Alberta Oil Sands Environmental Research Program by Canadian Forestry Service, Northern Forest Research Centre. AOSERP Report 46. 40 pp.

203. McLaughlin, S.B., D.C. West, H.H. Shugart and D.S. Shriner, 1978. Air pollution effects on forest growth and succession: applications of a mathematical model. Presented at 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas, June 25-30, 1978. 16 pp.

204. Constantinidou, H., T.T. Kozlowski and K. Jensen, 1976. Effects of sulphur dioxide on *pinus resinosa* seedlings in the cotyledon stage. Journal of Environmental Quality. 5(2):141-144.

205. Baker, J., D. Hocking and M. Nyborg, 1976. Acidity of open and intercepted precipitation in forests and effects on forest soils in Alberta, Canada. Proceedings of First International Symposium on Acid Precipitation in the Forest Ecosystem (1975). USDA Forest Service. General Technical Report NE-23.

206. Wride, M.C., 1975. The effect of SO_2 emissions on moose (*Alces alces*) in the Whitecourt area. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 153-160.

207. Greenhill, S., E.S.O. Smith, M. Grace, A. Kayani and B. Juchli, 1975. An evaluation of the health effects of air pollution in Alberta. University of Alberta, Department of Community Medicine, Edmonton. National Health Grant Project 608-7-121. 86 pp.

208. Hawkes, M.P.G., 1976. Health effects from kraft (sulphate) pulp mill operations. Environment Conservation Authority, Edmonton.

209. Colucci, A.V., 1977. Current status of knowledge relative to the health effects of SO_X. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 109-121.

210. Greenhill, S., 1978. Human health effects of hydrogen sulfide and sulfur dioxide. Alberta Department of the Environment, Edmonton. 42 pp.

211. Rogers, R.E., 1976. Hydrogen sulfide: a bibliography of its health effects, formation, distribution and control. Environment Conservation Authority, Edmonton. 19 pp.

212. Burnett, W.W., E.G. King, M. Grace and W.F. Hall, 1977. Hydrogen sulphide poisoning: review of 5 years' experience. Canadian Medical Association Journal. 117:1277-1280.

213. McKinnon, Allen and Associates (Western) Limited, 1977. Effects of airborne emissions from a gas processing plant on crops and livestock. Shell Canada Resources Limited, Calgary.

214. O'Donoghue, J.G. and F.E. Graesser, 1962. Effects of sulphur dioxide on guinea pigs and swine. Canadian Journal of Comparative Medicine and Veterinary Science. 26:255-263.

215. MacDonald, W.R. and R.F. Klemm, 1973. Selenium, animal health and sour gas plants. Environment Conservation Authority, Edmonton. 26 pp.

216. Elam, C.J., 1974. Sulphur requirements of ruminants. Alberta Department of Agriculture, Edmonton. 9 pp.

217. Hsu, H. and G.W. Hodgson, 1978. Depletion of selenium in sulphur emissions from sulphur-recovery gas plants. Environmental Science and Technology. 12:1039-1042.

218. Nordstrom, G.A. and J.B. McQuitty, 1976. Manure gases in the animal environment - a literature review (with particular reference to cattle housing). University of Alberta, Department of Agricultural Engineering. Research Bulletin 76-1.

219. Nordstrom, G.A., 1975. A study of calf response to ammonia and hydrogen sulfide gases. University of Alberta, Department of Agricultural Engineering. M.Sc. Thesis.

220. O'Donoghue, J.G., 1961. Hydrogen sulphide poisoning in swine. Canadian Journal of Comparative Medicine and Veterinary Science. 25:217-219.

221. Clanachan, A.S., 1979. H_2S toxicity analysis. Alberta Department of the Environment, Edmonton. 31 pp.

222. Western Research and Development Limited, 1977. Annual air monitoring report, 1977, Carstairs - Crossfield plant. Home Oil Company Ltd. 12 pp.

223. Western Research and Development Limited, 1972. A report on atmospheric corrosion station evaluation in the Petrogas processing plant and surrounding area, July, 1968 to February, 1972. Canadian Occidental Petroleum Ltd. 21 pp.

224. Cassidy, M., 1978. Atmospheric corrosion rates in the vicinity of the Petrofina Canada Limited Wildcat Hills plant, December 16, 1976 to January 16, 1978. Petrofina Canada Ltd. 13 pp.

225. Western Research and Development Limited, 1977. Atmospheric corrosion rates in the vicinity of the Petrofina Canada Limited Wildcat Hills gas plant, January 30, 1976 to January 6, 1977. Petrofina Canada Ltd. 15 pp.

226. Western Research and Development Limited, 1979. Atmospheric corrosion rates in the vicinity of the Wimborne gas plant. Mobil Oil Canada Ltd.

227. Western Research and Development Limited, 1979. Atmospheric corrosion rates in the vicinity of the Petrofina Canada Limited Wildcat Hills gas plant, January 16, 1978 to March 13, 1979. Petrofina Canada Ltd.

228. Das, N.C. and W.E. Kortsch, 1977. Review of analytical methods used for the determination of sulphur compounds in the environment. Proceedings of Alberta Sulphur Gas Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 267-381.

229. Weaver, R.S., W. Lawson and W.J. Fenrick, 1974. Some problems in measuring air pollutants in clean atmospheres (u). Defense Research Establishment Suffield: Ralston: Alberta. Project No. 99-30-15. Report No. 277. 21 pp.

230. Krouse, H.R., 1977. Sulphur isotope studies and their role in petroleum exploration. Journal of Geochemical Exploration. 1:189-211.

231. Krouse, H.R., 1977. Sulphur isotope abundances elucidate uptake of atmospheric sulphur emissions by vegetation. Nature. 265:45-46.

232. Krouse, H.R., 1979. Sulphur isotopes in our environment. Natural Isotopes in Environmental Studies. P. Fritz and J. Ch. Fontes (Eds.). Elsevier.

233. Krouse, H.R., 1978. Sulphur isotopes in the environment: Teepee Creek gas plant. Alberta Department of the Environment, Research Secretariat, Edmonton. Report 1979/1. 58 pp.

234. Canada Department of the Environment, 1979. Natural inventory of natural sources and emissions of sulphur compounds. EPS Report 3-AP-79-2, May 1979 (unpublished).

235. Penney, D.C., 1979. Sulphur fertilizer sales in Alberta 1974-1978. Alberta Department of Agriculture, Edmonton (private communication).

236. Government of the Province of Alberta, 1975. Clean Air (maximum levels) Regulations A.R. 218/75.

237. Federal - Provincial Committee on Air Pollution, 1976. Criteria for national air quality objectives. Fisheries and Environment Canada. 41 pp.

9.2 UNCITED REFERENCES

Bertrand, R.A., 1973. Reclaiming of soils made barren by sulphur gas processing plants. University of Alberta, Department of Soil Science, Edmonton. M.Sc. Thesis. 176 pp.

Blauel, R.A. and D. Hocking, 1973. Sulphur gas impact surveys and research at the Northern Forest Research Centre. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 1, 1973. Canada Department 4th Environment, Northern Forest Research Centre, Edmonton, pp. 111-114.

Croft, B.R., A. Lamb, and R.N. Dawson, 1977. Preliminary investigation into the magnitude of fog occurrence and associated problems in the oil sands area. Prep. for the Alberta Oil Sands Environmental Research Program by Stanley Associates Engineering Ltd. AOSERP Report 9. 87 pp.

Intera Environmental Consultants Limited, 1975. An impact assessment of forest vegetation and soils within a seven mile radius of the Great Canadian Oil Sands complex. Great Canadian Oil Sands.

Khan, A.A. and G.R. Webster, 1968. Sulphate distribution in solonetzic soil with a water table. Journal of Soil Science. 19:19-24.

Laishley, E.J., M.G. Tyler and R.G. McCready, 1978. Environmental assessment of soils in contact with sulfur-based construction material. Environmental Biogeochemistry and Geomicrobiology. Volume 2: The Terrestrial Environment. Ann Arbor Science Publishers Inc., Ann Arbor, Michigan. pp. 699-705.

Legge, A.H., 1973. Design of a gas exchange system for the study of effects of sulphur doxide on vegetation. Proceedings of Alberta Sulphur Gas Research Workshop I, Edmonton, Alberta, November 1, 1973. Canada Department of the Environment, Northern Forest Research Centre, Edmonton. pp. 115-118.

Lowe, L.E., 1969. Forms of sulphur in soils. Report of Meeting of National Soil Fertility Committee, Western Section. pp. 72-80.

McCready, R.G.L., E.J. Laishley and H.R. Krouse, 1974. The effect of sulphate and sulphate on growth and sulphur isotope fractionation by *Clostridium pasteurianum*. Proceedings of Sulphur Symposium 1974. University of Calgary. pp. F1-F10.

Mohtadi, M.F. and R.D. Rowe, 1973. A rational strategy for control of SO_2 emission in Alberta. Presented at 4th Joint Chemical Engineering Conference, Vancouver, B.C., September 9-12, 1973. 24 pp.

Murray, W.A. and J. Kurtz, 1976. A study of potential ice fog and low temperature water fog at Mildred Lake, Alberta. Syncrude Canada Ltd., Edmonton. 63 pp.

Nyborg, M., 1978. Report on the project "Fate of emitted sulphur dioxide", conducted April, 1973 to March, 1976. Alberta Environmental Research Trust, Edmonton. 70 pp.

Ratanalert, P., J.M. Crepin and C.F. Bentley, 1978. Soil tests for sulfur: importance and limitations. Agriculture and Forestry Bulletin. 1(4):16-21.

Shipley, B.L., 1977. Technique and preliminary success of using a hydro seeder for lime application to forested areas near a sulphur storage facility in Alberta. Proceedings of Alberta Sulphur Gas Research Workshop III, Edmonton, Alberta, November 17-18, 1977. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 213-218.

Sibbald Group, 1977. Interpretation of soils and vegetation from aerial photographs in the Big Bend, Alberta plant site area. Candel Oil Limited.

Thompson, M.D., 1975. Preliminary investigations on the use of thermal imagery for the detection of sulphur dioxide stressed vegetation. Proceedings of Alberta Sulphur Gas Research Workshop II, Kananaskis, Alberta, January 16-17, 1975. Alberta Department of the Environment, Research Secretariat, Edmonton. pp. 122-133.

Walker, D.R., 1972. Soil sulphate I. Extraction and measurement. Canadian Journal of Soil Science. 52:253-260.